Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Linking the International System of Units to Fundamental Constants:

Precision Experiments for the Revised SI

Joachim H. Ullrich

President of PTB, Physikalisch-Technische Bundesanstalt

Vice President of the CIPM

President of the Consultative Committee of Units

Vice President of DIN, the German Standardisation Organisation

Virtual Seminar on Precision Physics and Fundamental Symmetries, 18/06/2020

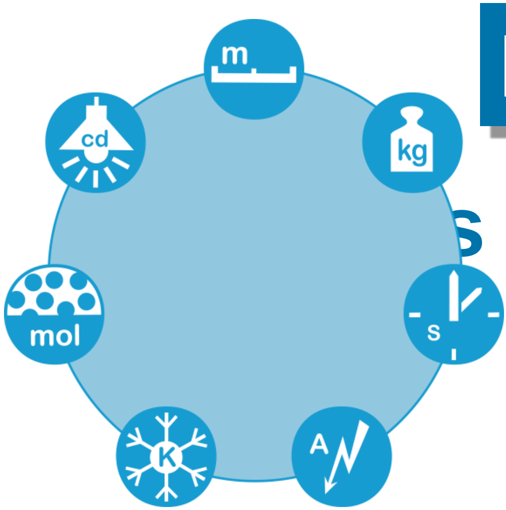
Linking the International System of Units to Fundamental Constants:

Precision Experiments for the Revised SI

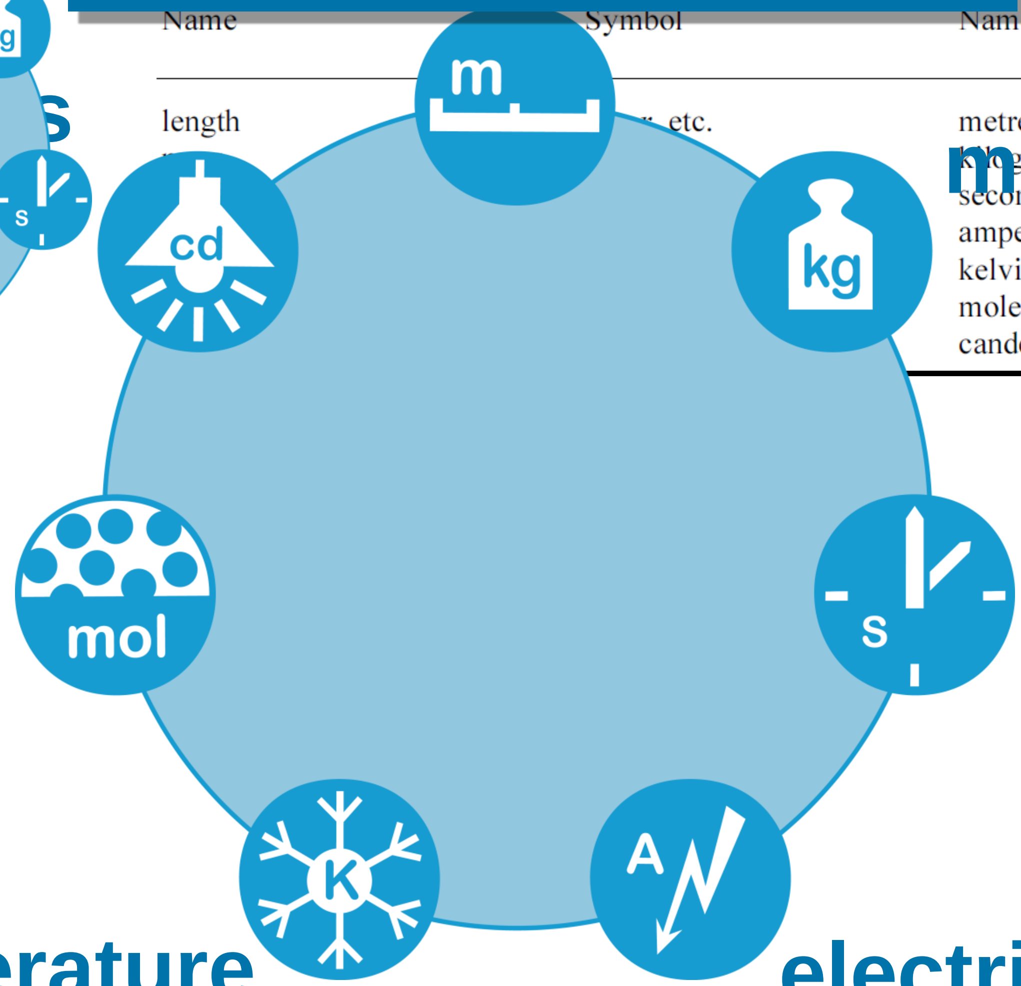
1. The international system of units: SI
2. Defining constants for the revised SI
3. About the future of time

The International System of Units: SI

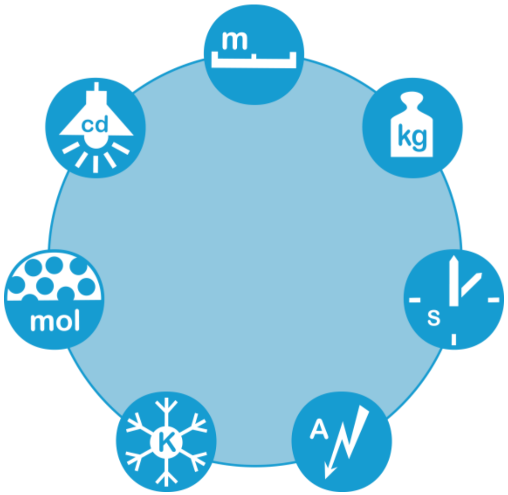
Established in 1960: CGPM



		...ase unit	
Name	Symbol	Name	
length	... etc.	metre	
		kilogram	kg
		second	s
		ampere	A
		kelvin	K
		mole	mol
		candela	cd



The International System of Units: SI



Base units

		SI base unit	
Name	Symbol	Name	Symbol

Derived units with special names

Dimensions of quantities

→ A set of coherent SI units

		Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units
			1 (b)	m/m
			1 (b)	m^2/m^2
				s^{-1}
force	newton	N		$m\ kg\ s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
energy, work, amount of heat	joule	J	N m	$m^2\ kg\ s^{-2}$
power, radiant flux	watt	W	J/s	$m^2\ kg\ s^{-3}$
electric charge, amount of electricity	coulomb	C		s A
electric potential difference, electromotive force	volt	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
capacitance	farad	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
electric resistance	ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
inductance	henry	H	Wb/A	

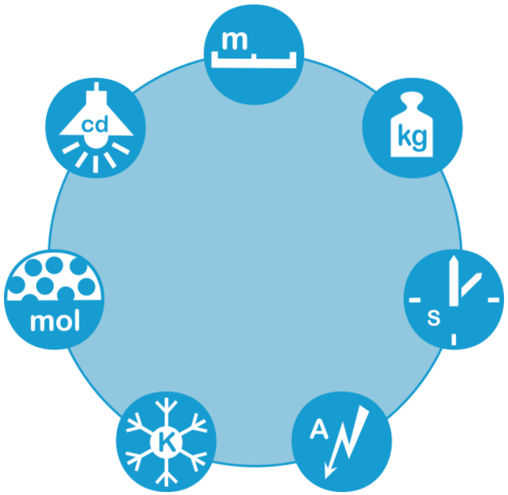
frequency	hertz (d)	Hz	s^{-1}
force	newton	N	$m\ kg\ s^{-2}$

Derived units

$[v] = m\ s^{-1}$

$[c] = mol\ m^{-3}$

The International System of Units: SI

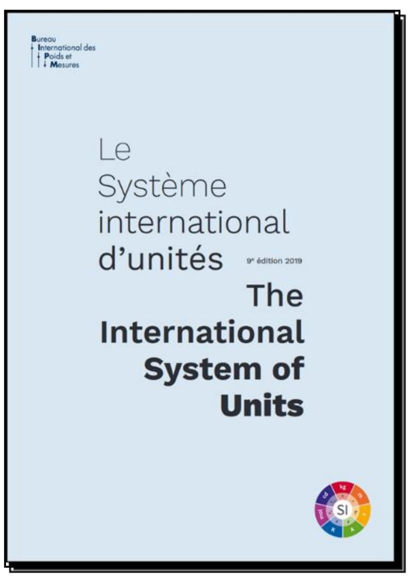


Base units

Derived units

Dimensions of quantities

→ A set of coherent SI units


Bureau International des Poids et Mesures

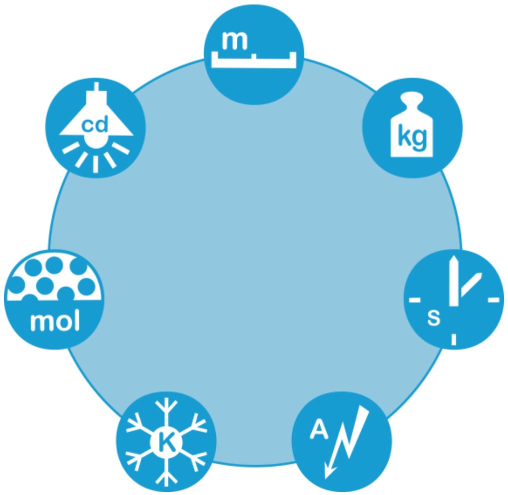
Le Système international d'unités

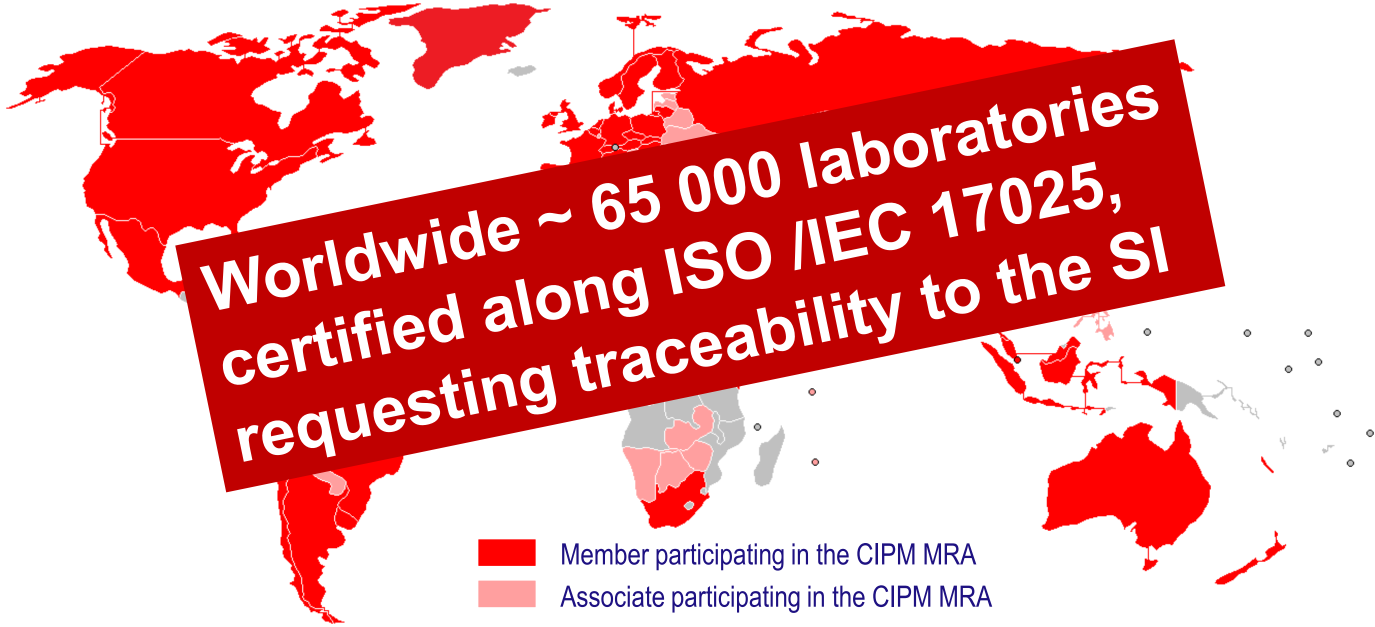
9e édition 2019

The International System of Units

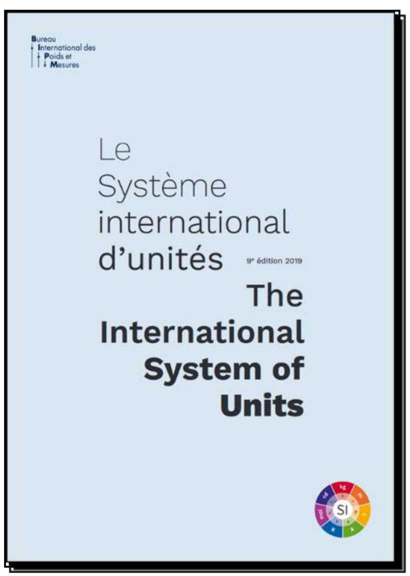
- A global measurement infrastructure
- Valid world wide
  - Intensity of light from an LED
  - CO_2 concentration in the air
  - Creatinine concentration in blood serum
  - Dose equivalent outside nuclear reactors
  - ....

The International System of Units: SI





Worldwide ~ 65 000 laboratories certified along ISO /IEC 17025, requesting traceability to the SI



- A global measurement infrastructure
- Valid world wide: CIPM-MRA signed by

→ 97.6 % of the world economy

→ The cornerstone of international quality infrastructure (QI)

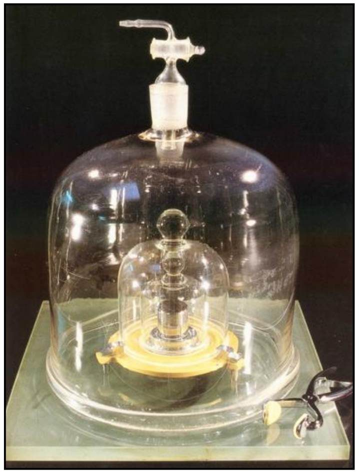
Quantities and measurement units

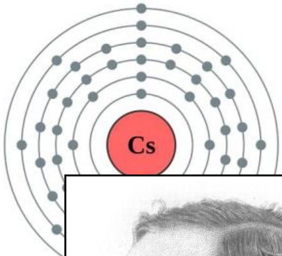
Value of a quantity → $Q = \{Q\}\ [Q]$ ← number, unit

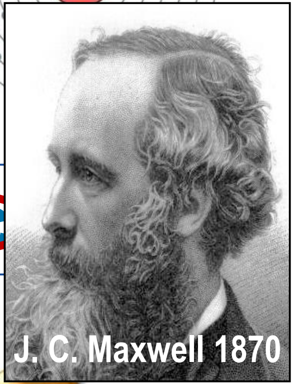
$m = 10.1(2)\,\mathrm{kg}$

$t = 55.4(1)\,\mathrm{s}$

artefact







$$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\,192\,631\,770\ \mathrm{s}^{-1}$$

Constant of nature

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}}$$

"Take properties of atoms, not those of the Earth"

Define a unit by fixing the numerical value of a constant of nature

$$l_P = \sqrt{\frac{\hbar G}{c^3}} = 1.61 \cdot 10^{-31}\, m$$

$$m_P = \sqrt{\frac{\hbar c}{G}} = 2.17 \cdot 10^{-8}\, kg$$

$$t_P = \frac{l_P}{c} = 5.39 \cdot 10^{-44}\, s$$

$$T_P = \frac{m_P c^2}{k} = 1.41 \cdot 10^{32}\, K$$

von Max Planck.

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Aus-

...with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their validity for all times and civilisations, even extraterrestrial and nonhuman...

1900. № 1.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 1.

irreversible Strahlungsvorgänge;

von Max Planck.

Dem gegenüber dürfte es nicht ohne Interesse sein zu bemerken, dass mit Zuhülfenahme der beiden in dem Aus-

dr... un... Ze... sp... Ze... Cu... lic...

…with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their validity for all times and civilisations, even extraterrestrial and nonhuman…

SI International System of Units

A consistent

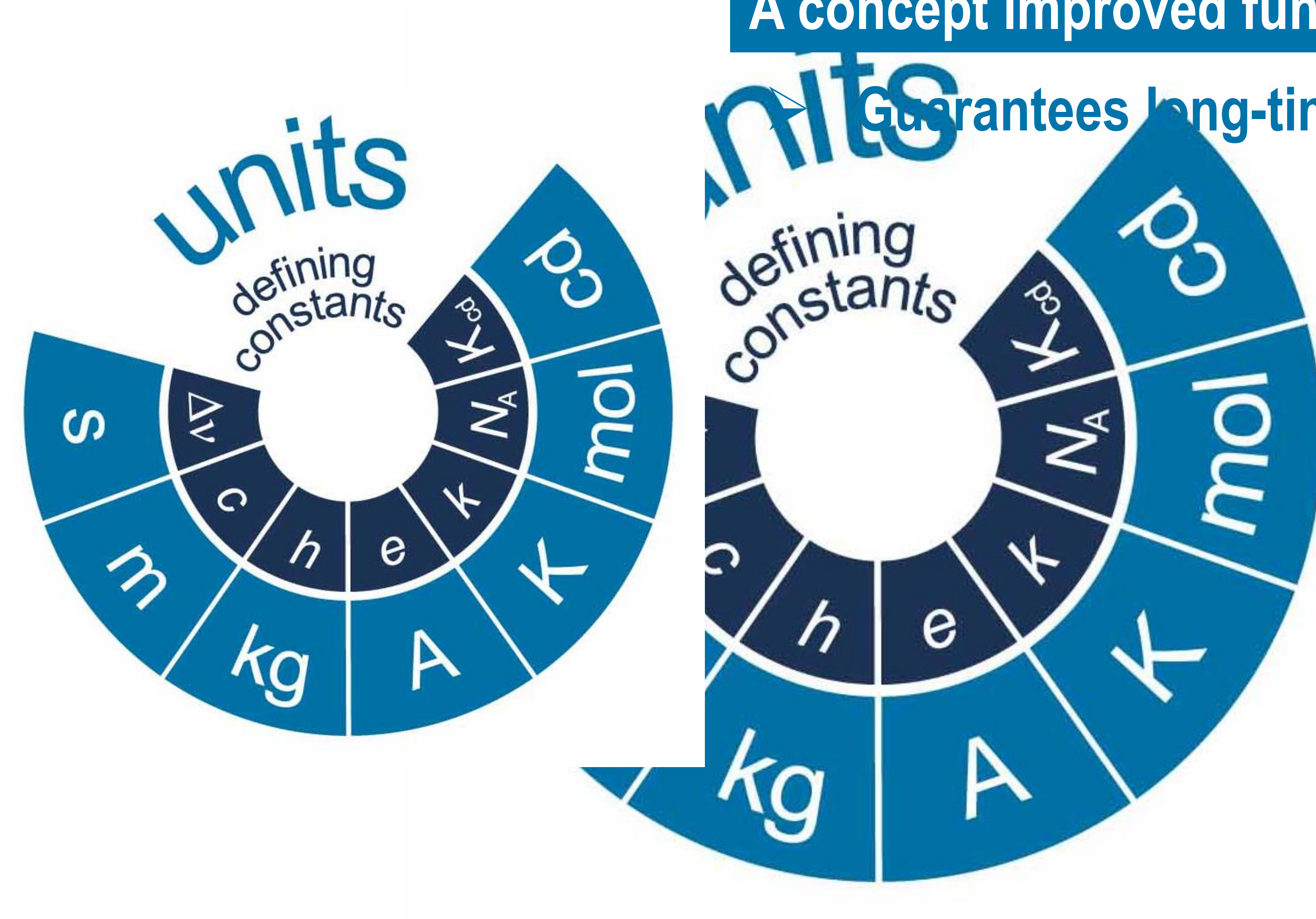
and coherent set:

based on our present understanding of nature

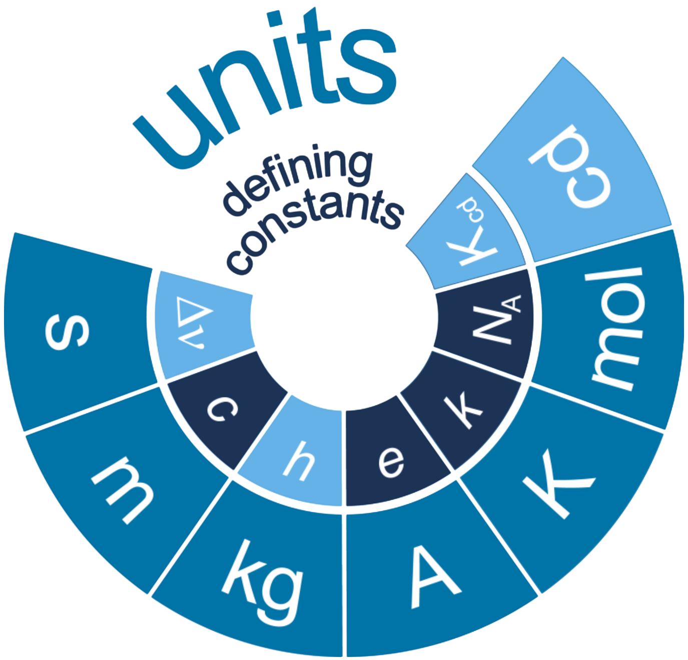
Revised International System of Units

A concept improved fundamentally!

- Guarantees long-time stability



Revised International System of Units



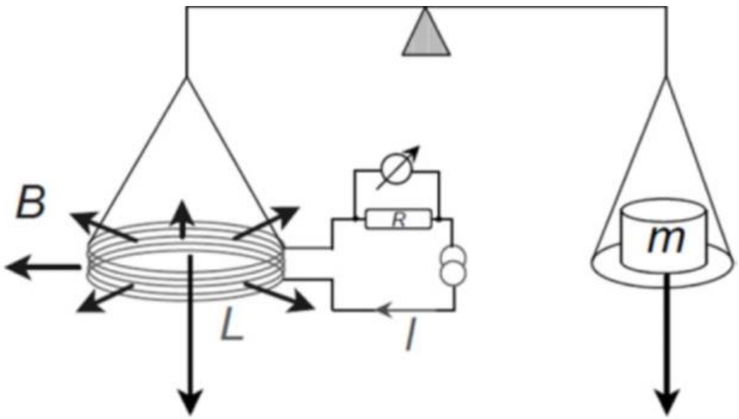
A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general

Revised International System of Units

Watt balance or Kibble balance

…damentally!

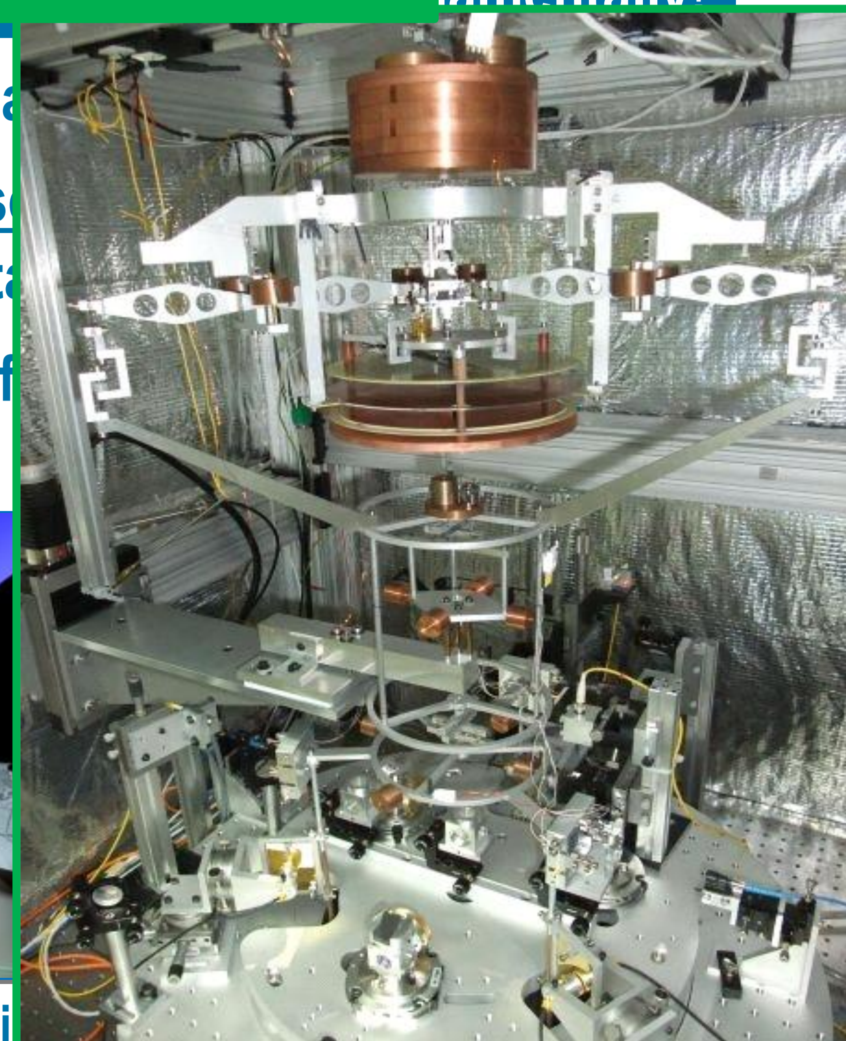


Gua…

A s…

esta…

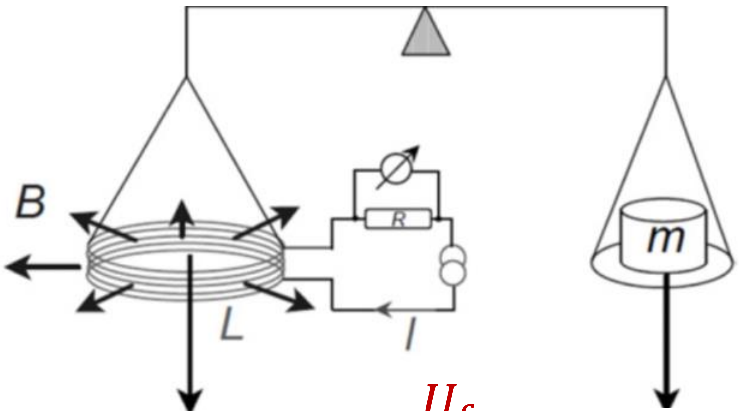
Diff…



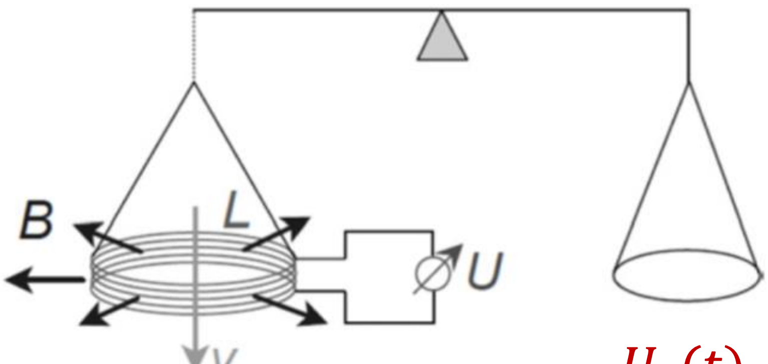
“Si…

Revised International System of Units

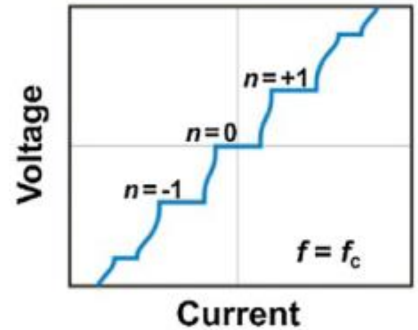
Watt balance or Kibble balance



$$F = Bl \cdot I = Bl \cdot \frac{U_f}{R_f} = m \cdot g$$



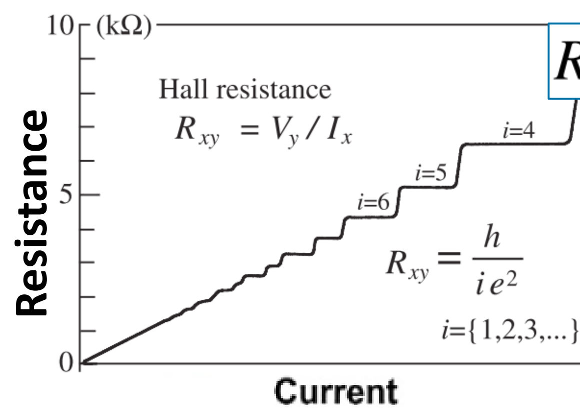
$$U_v(t) = Bl \cdot v(t) \qquad Bl = \frac{U_v(t)}{v(t)}$$



$$K_J = 2e/h$$

$$m \cdot g = \frac{U_v(t)}{v(t)} \cdot \frac{U_f}{R_f} \propto h$$

$$R_K = h/e^2$$



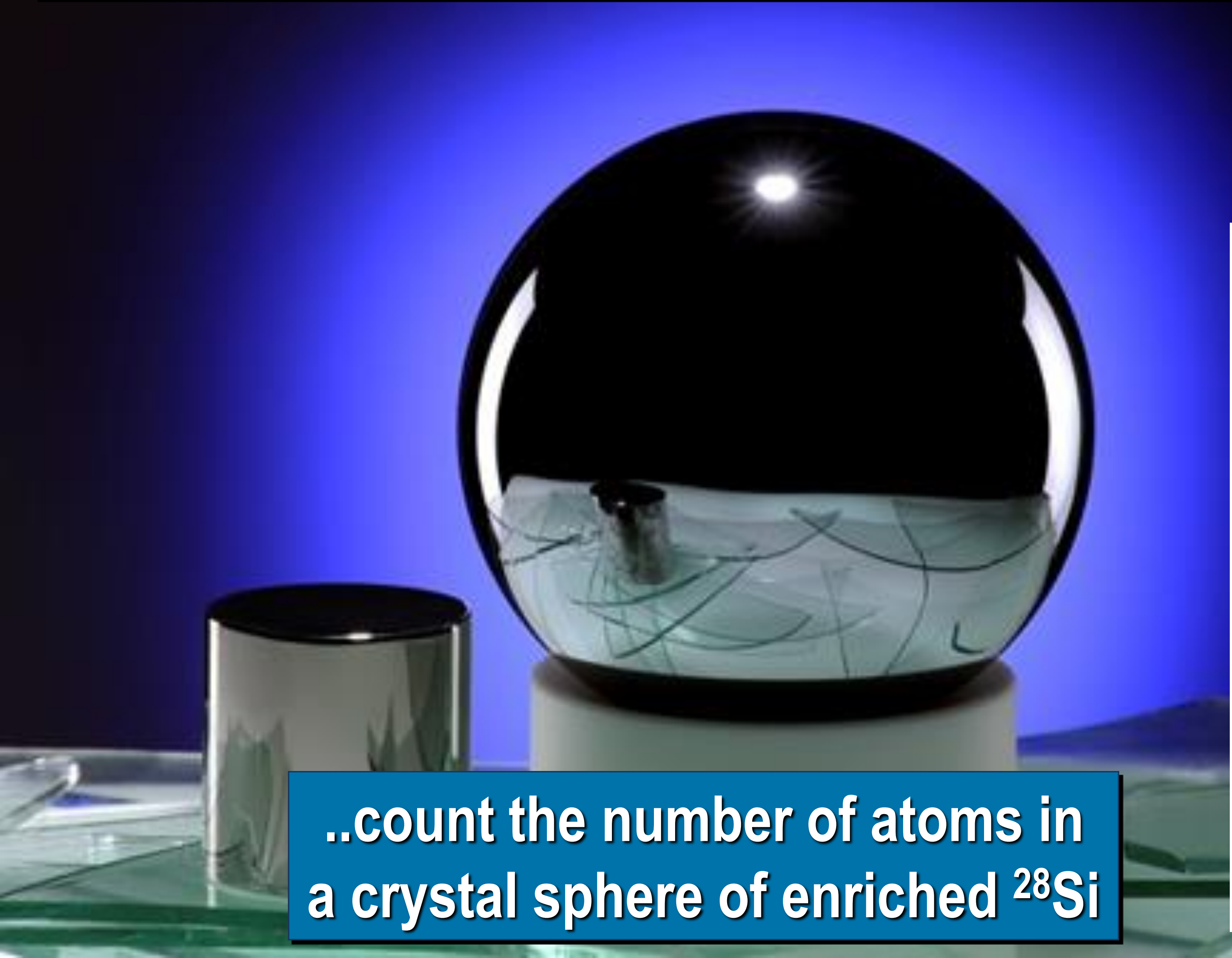
Revised International System of Units

Commercial primary Kibble Balances

- "off-the-shelve" components
- high precision
- industrial application: E1, E2
- "self-calibrating"
- connected to the IoT

Version	Mass range	MPE OIML R111-1	$U_r \leq 1/3 \cdot$MPE k=2	Environment
PB 2 (E2)	1 mg…100 g	$16 \cdot 10^{-7}$	$5.3 \cdot 10^{-7}$	Air
PB 1 (E1)	1 mg…1 kg	$5 \cdot 10^{-7}$	$1.7 \cdot 10^{-7}$	High Vacuum

The Silicon Route: Avogadro Collaboration



..count the number of atoms in a crystal sphere of enriched ^{28}Si

Bureau International des Poids et Mesures

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

irmm Institute for Reference Materials and Measurements

NIST

Australian Government National Measurement Institute

NMIJ

NPL National Physical Laboratory

PTB

The Silicon Route

$$m_{sphere} = \frac{8V}{a^3} \cdot \frac{2hR_\infty}{c\alpha^2} \cdot \frac{\sum_i f_i A_r^i}{A_r^e}$$

relative mass of Si / relative electron mass

number of atoms

electron mass

$u_{rel}(\alpha) = 1.5 \cdot 10^{-10}($

$u_{rel}(R_\infty) = 1.9 \cdot 10^{-12}$

quantum theory of the hydrogen atom

IOP Publishing — Metrologia

Metrologia 49 (2012) L25–L27 — doi:10.1088/0026-1394/49/6/L25

LETTER TO THE EDITOR

The silicon route to a primary realization of the new kilogram

Jörn Stenger and Ernst O Göbel

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

Bureau International des Poids et Mesures

INRiM Istituto Nazionale di Ricerca Metrologica

irmm Institute for Reference Materials and Measurements

NIST

Australian Government National Measurement Institute

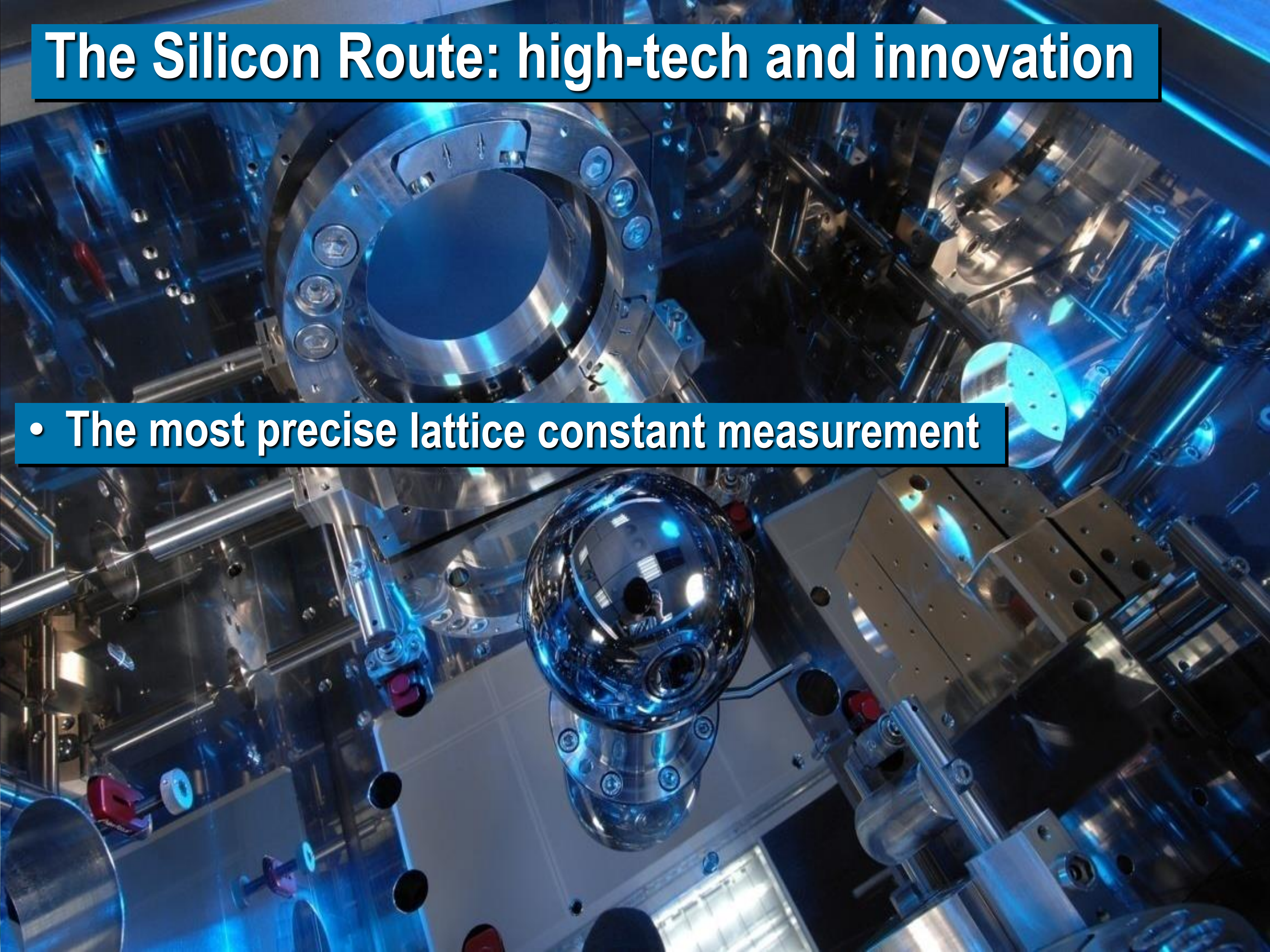
NMIJ

NPL National Physical Laboratory

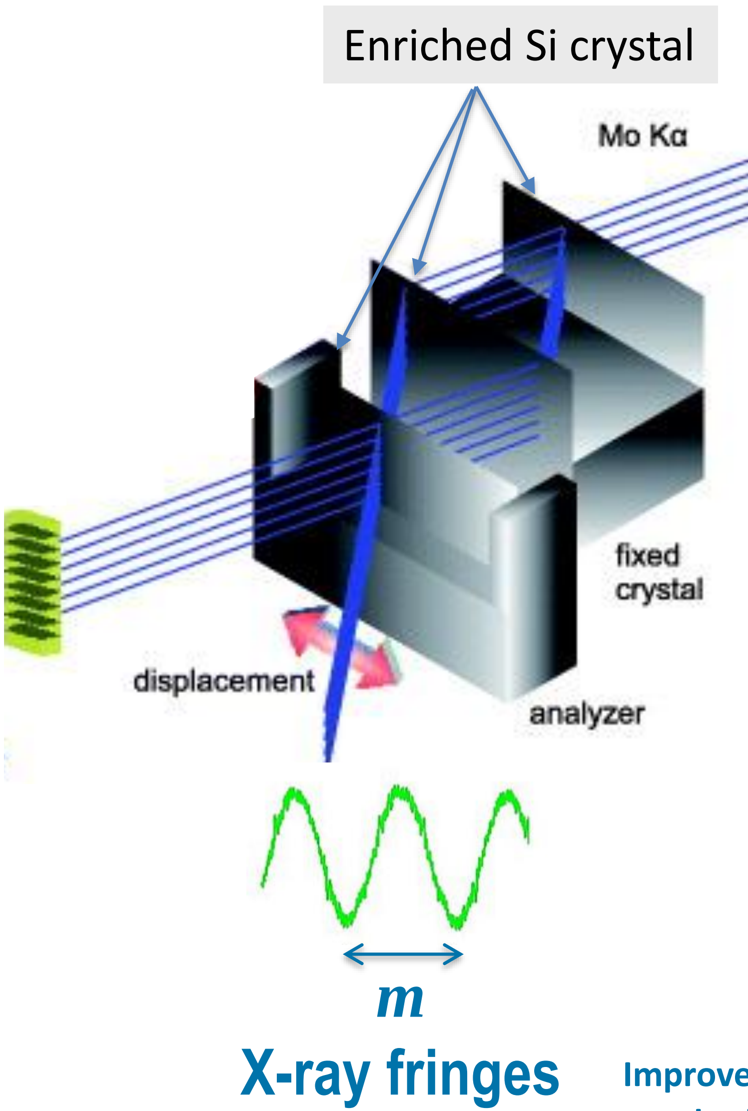
PTB

The Silicon Route: high-tech and innovation

- The most precise lattice constant measurement



lattice constant measurement



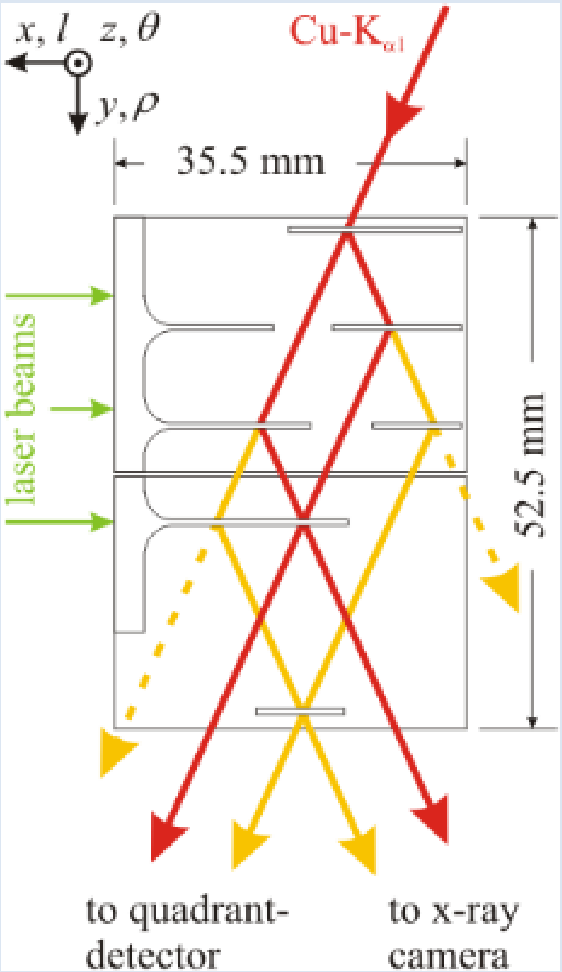
$$d_{220} = \frac{n}{m+x} \cdot \frac{\lambda_{opt}}{2}$$

$$u_{rel}\,(d_{220}) = 5 \cdot 10^{-9}$$

Improved measurement results for the Avogadro constant using a ^{28}Si-enriched crystal
Y. Azuma *et. al.*, Metrologia 52 (2015) 360

lattice constant measurement: COXI

X-ray interferometer:

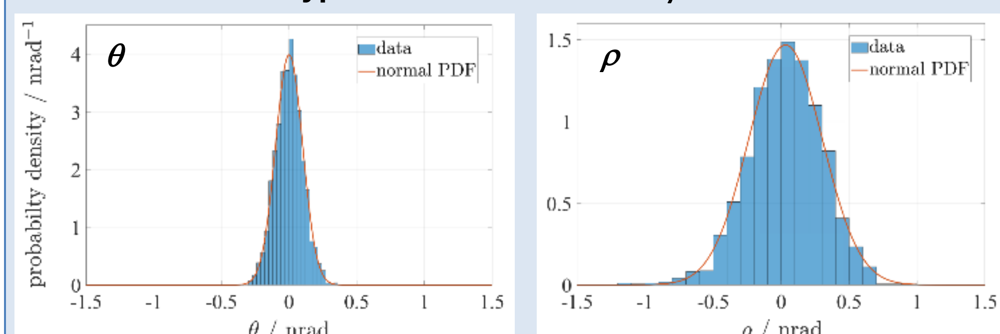


Goal: measure ^{28}Si lattice parameter at $u_{rel}(d_{220}) \leq 3\cdot10^{-9}$

PTB experimental concept successfully demonstrated: continuously scanning und synchronously measuring **x-ray** and **optical interferometer**

- **sub-nrad control of two angles θ and ρ** required during translation
- **minimization of Abbe errors successful**

Typical Results for θ and ρ:

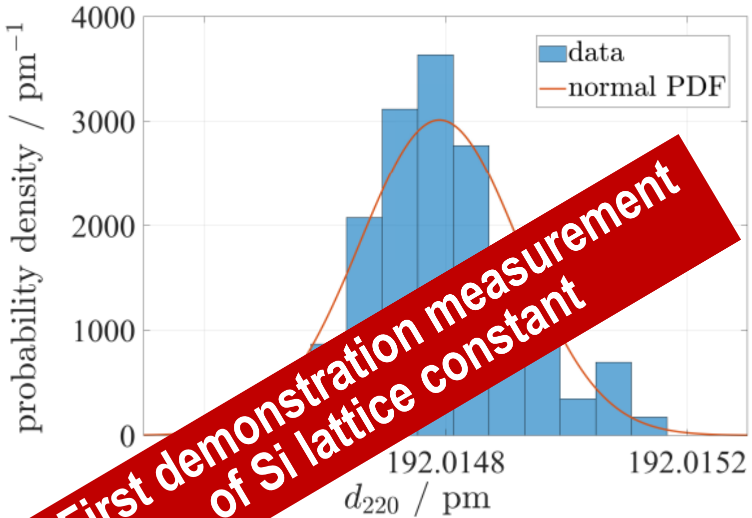


published: https://doi.org/10.1088/1361-6501/ab9b60

lattice constant measurement: COXI

Optical heterodyne interferometer

- Low phase noise > 500 Hz
- High scanning speed

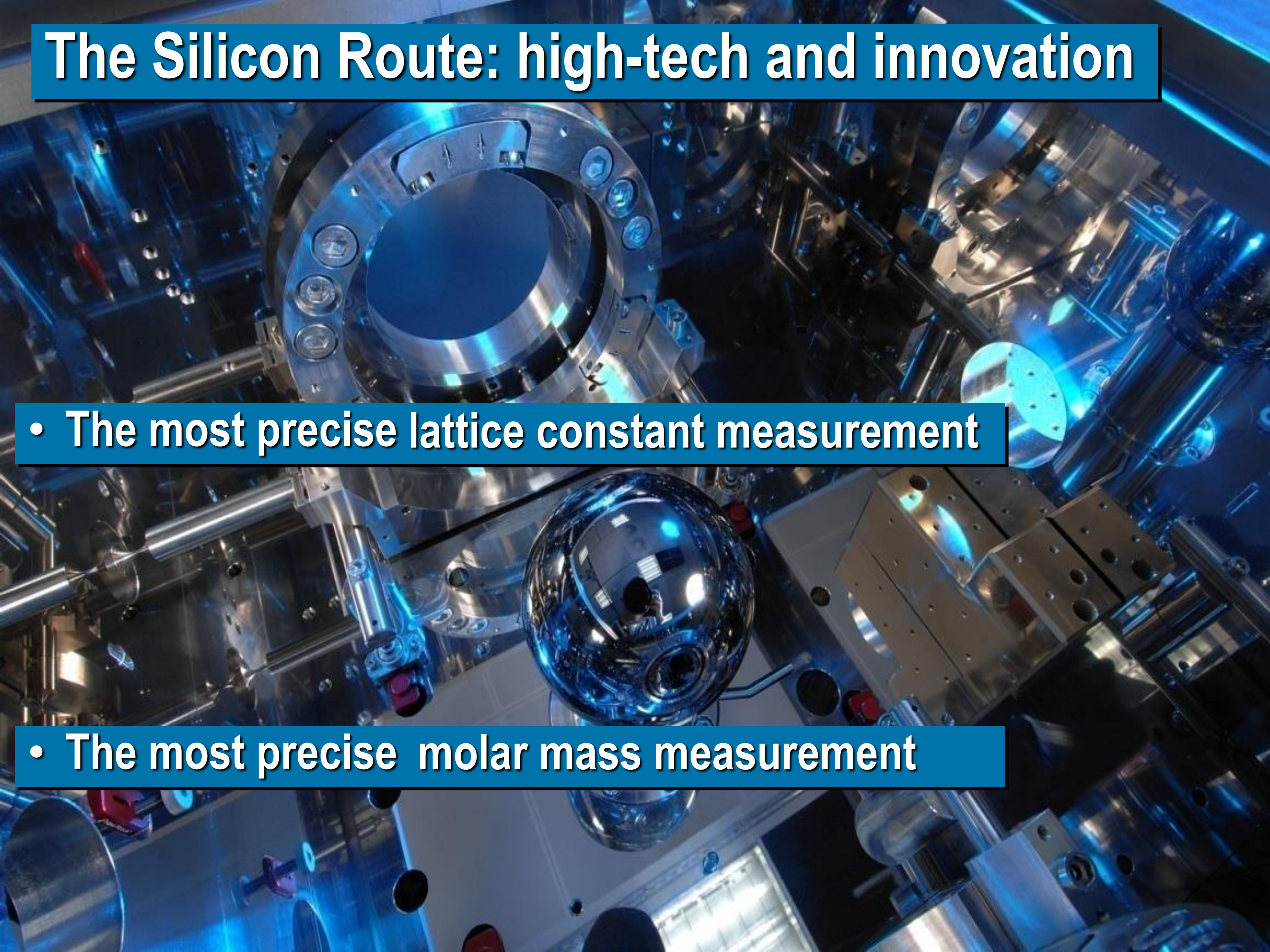


…: small scanning range of only 4 µm, …mperature control not yet implemented, uncorrected values only

Next steps in 2020:

- improvement of the optical alignment by a combined beam imager and autocollimator
- extension of the translation range to 500 µm
- final setup and calibration of the temperature measurement

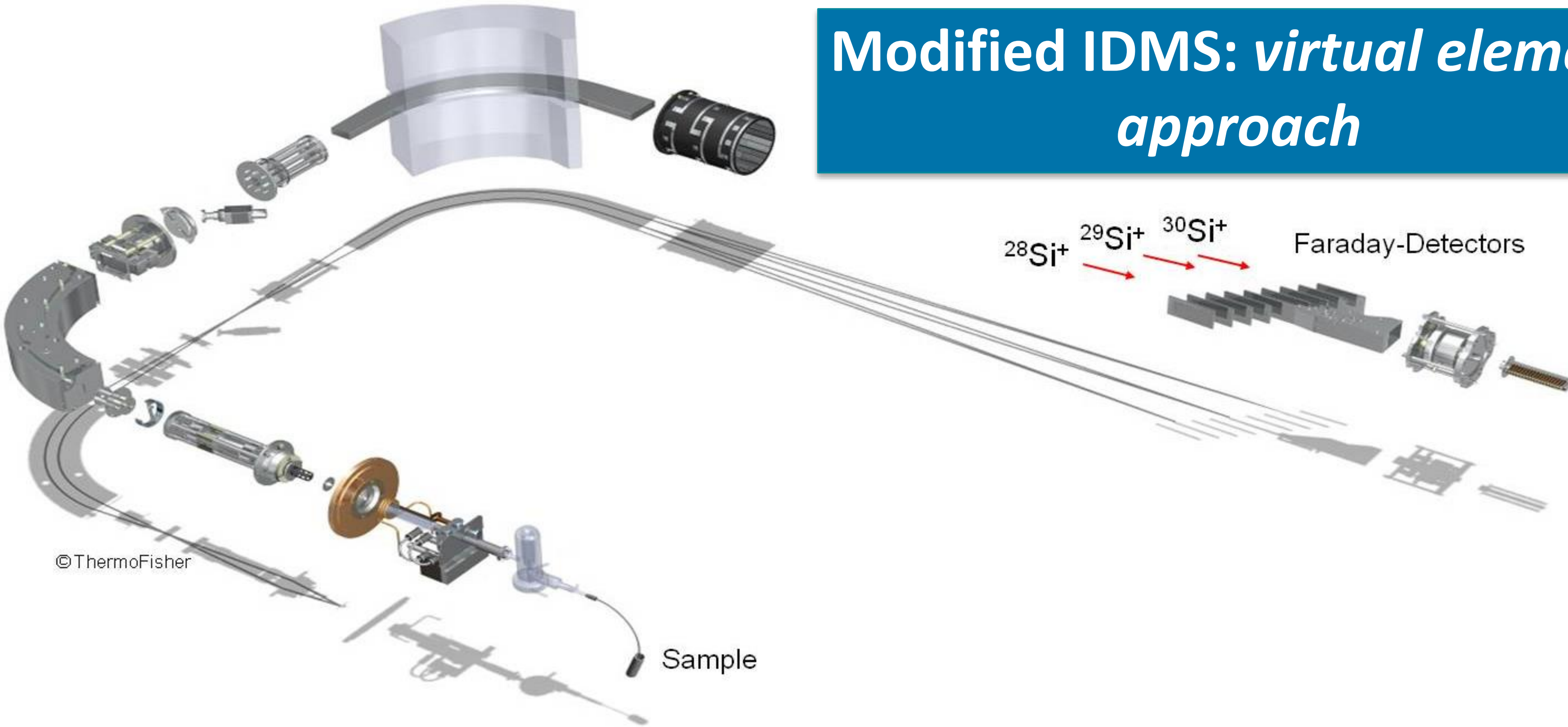
The Silicon Route: high-tech and innovation



- The most precise lattice constant measurement
- The most precise molar mass measurement

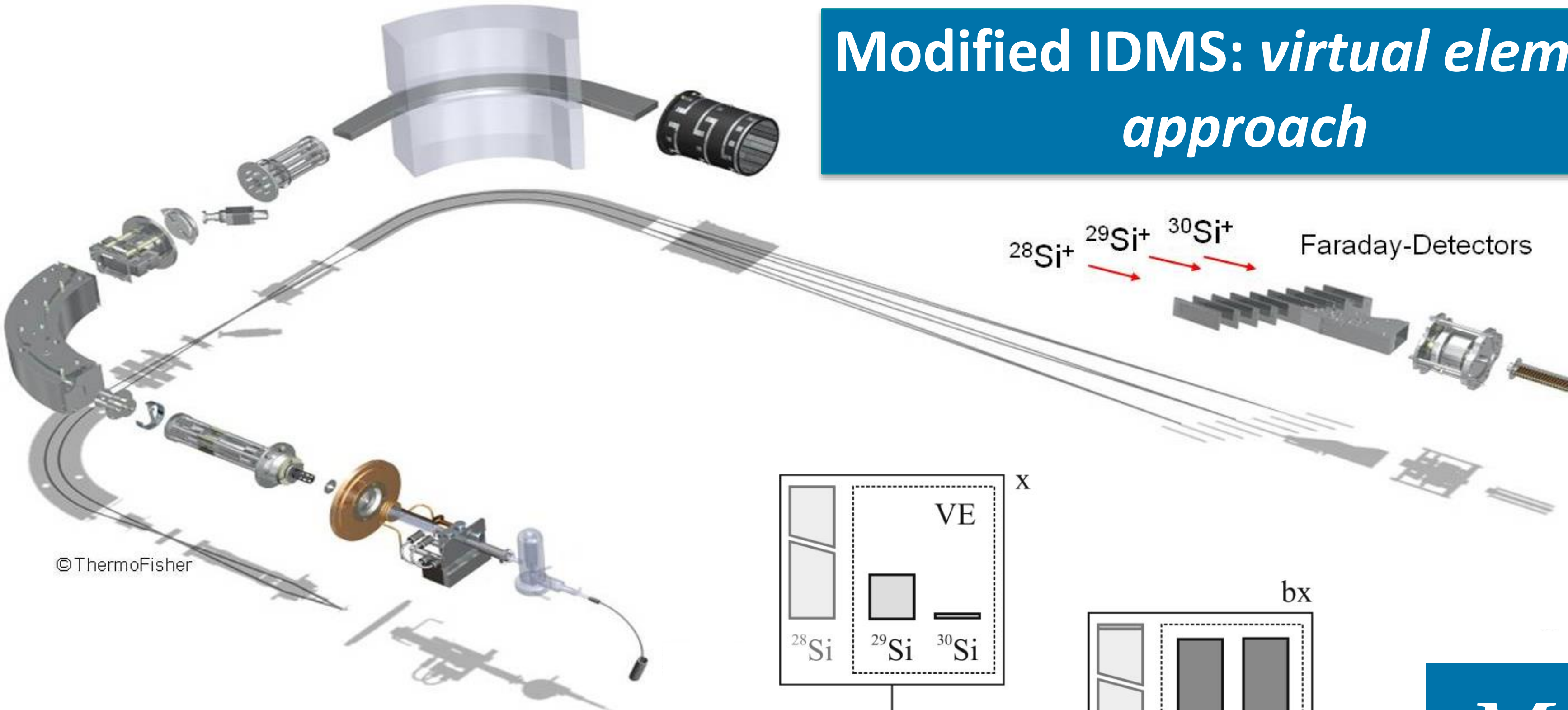
molar mass measurement

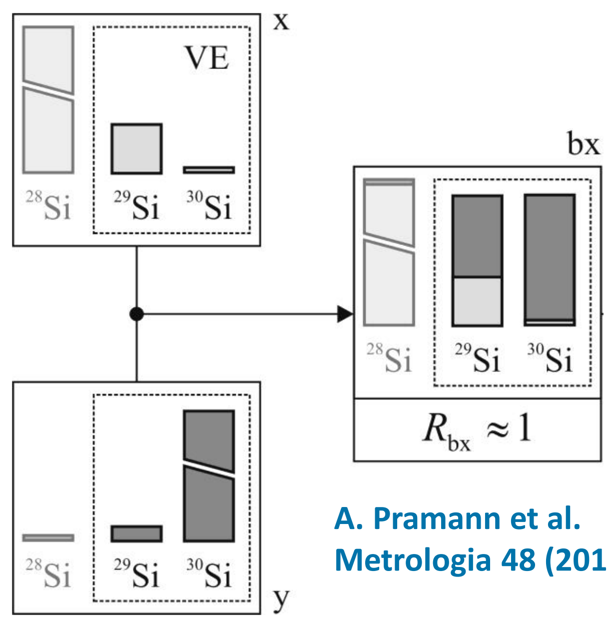
Modified IDMS: *virtual element approach*



molar mass measurement

Modified IDMS: *virtual element approach*





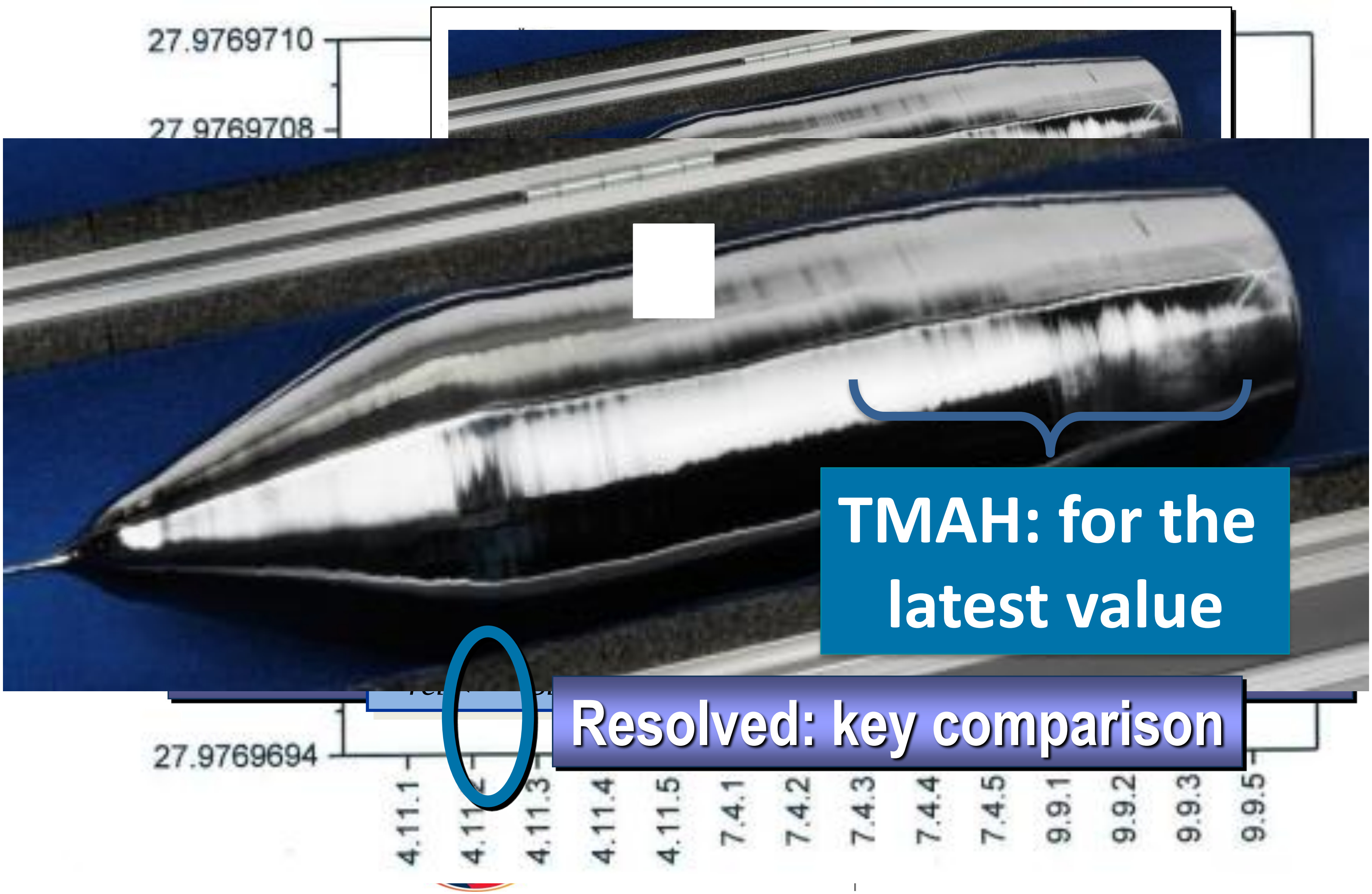
M_{Si}

A. Pramann et al.
Metrologia 48 (2011) S20-S25

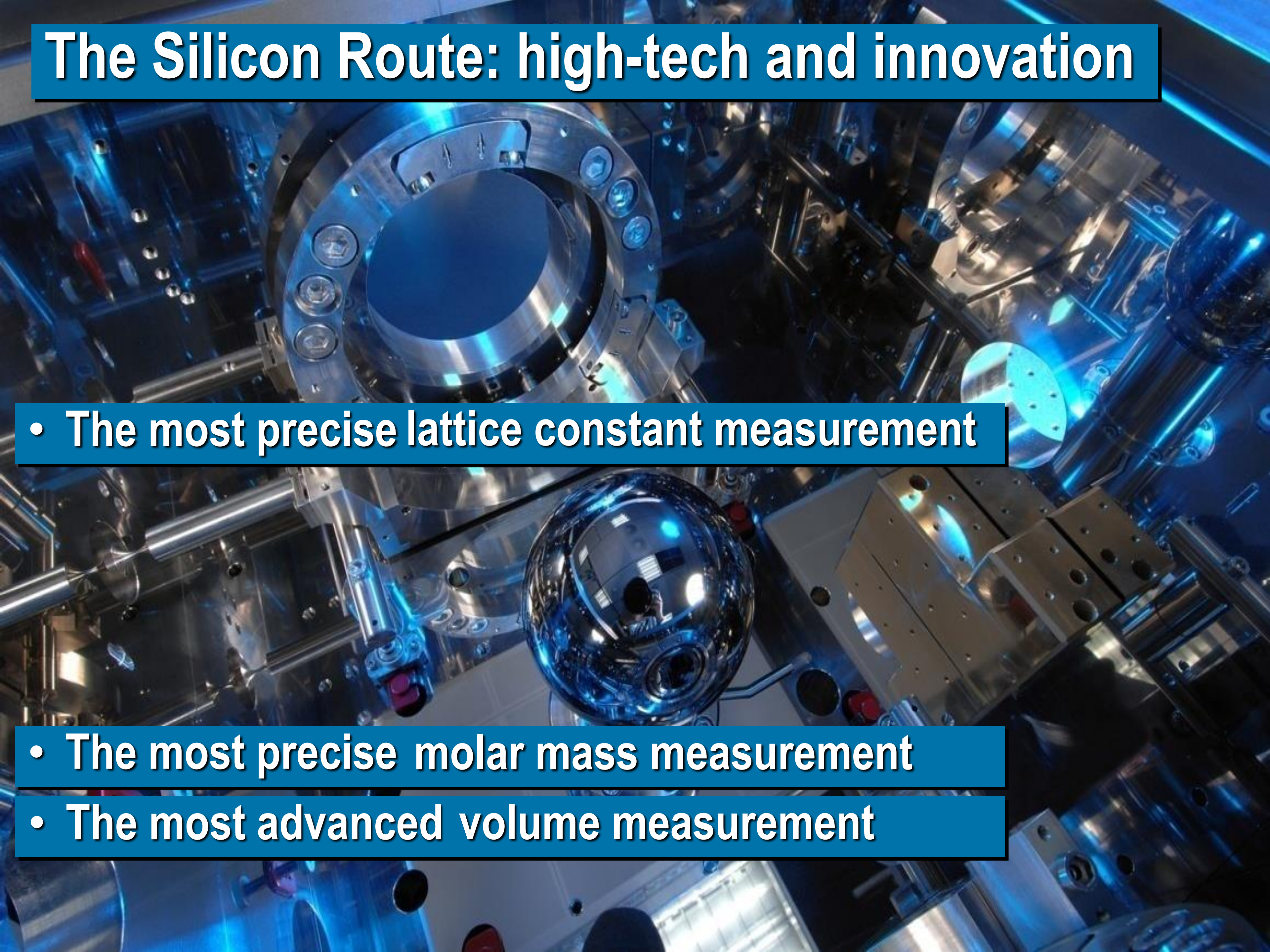
Si virtual element appoach

- **three samples: ^{28}Si-material („*x*“)**
  ^{30}Si-enriched („*y*“)
  IDMS-blend („*bx*“)
- **$R(^{30}Si/^{29}Si)$ measured in *x*, *y*, *bx***

molar mass measurement



The Silicon Route: high-tech and innovation



- The most precise lattice constant measurement
- The most precise molar mass measurement
- The most advanced volume measurement

volume measurement

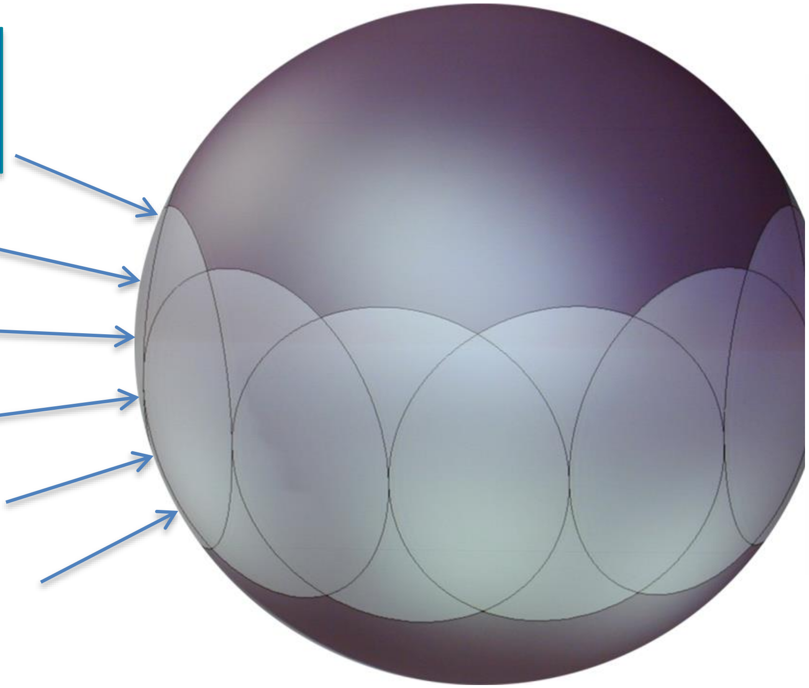
PTB Fizeau interferometer: sphere topography determination

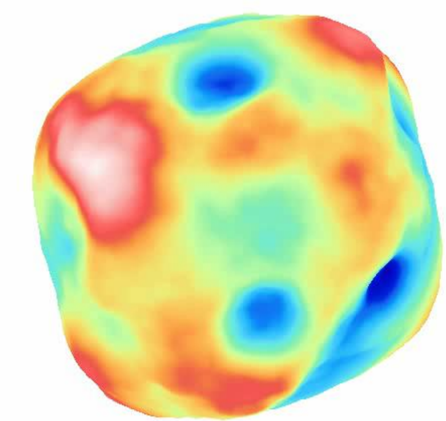
- extended beams with spherical wave fronts
- simultaneous measurement of some thousand diameters
- measurement uncertainty < 0.75 nm

complete coverage by 25-49 measurements

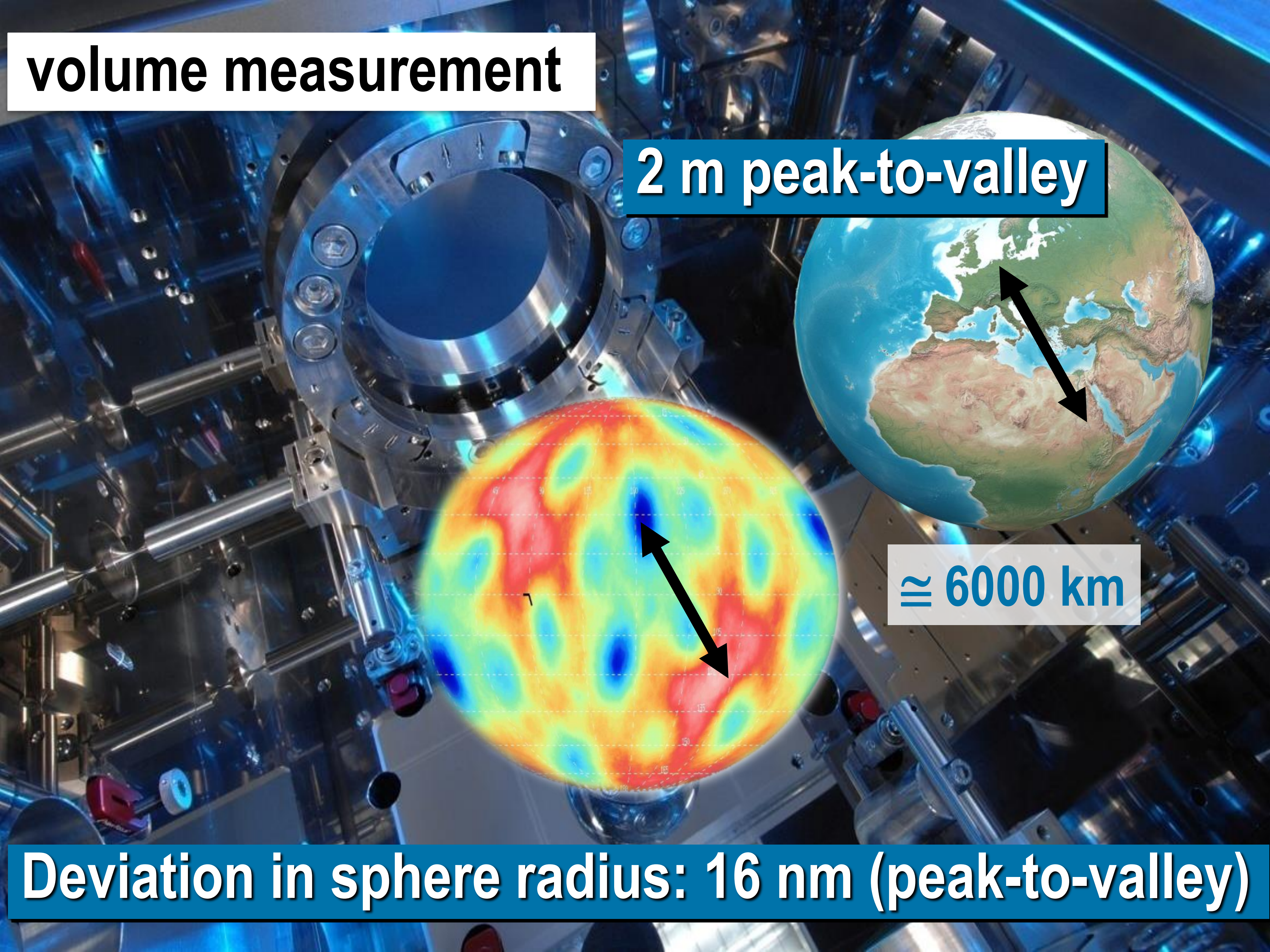
some 100 000 diameters

fit to some 2000 spherical harmonics

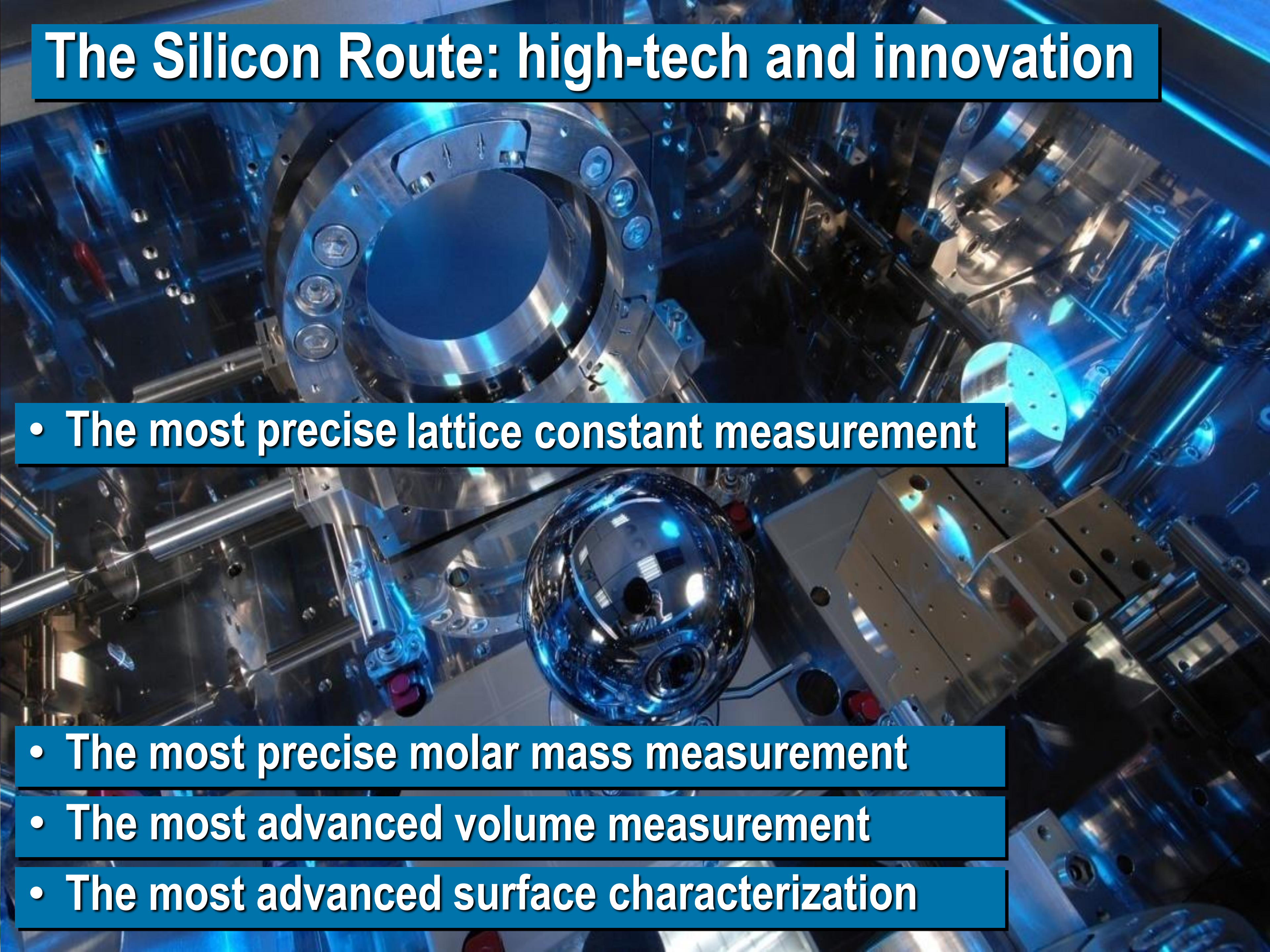




volume measurement



Deviation in sphere radius: 16 nm (peak-to-valley)



The Silicon Route: high-tech and innovation

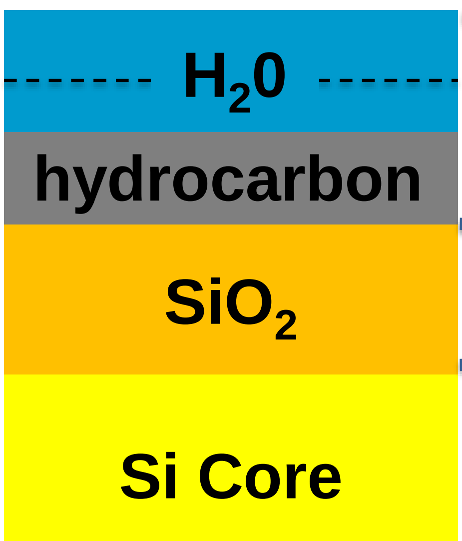
- The most precise lattice constant measurement
- The most precise molar mass measurement
- The most advanced volume measurement
- The most advanced surface characterization

surface characterization

For h, N_A determination: mass of the core of the Si-28 sphere

$$m_{core} = m_{meas} - m_{oxide} - m_{ads}$$

$$m_{ads} = m_{hydrocarbon} + m_{water(rev)} + m_{water(irrev)}$$



Thickness	Mass	Method
~0.4 (1) nm	~12 (3) µm	gravimetry
~0.3 (1) nm	~ 8 (2) µm	gravimetry
~0.6 (2) nm	~15 (6) µm	XRF
~1.0 (2) nm	~60 (13) µm	XRR/XRF/SE

adsorbents

oxide

Contamination → removed by cleaning

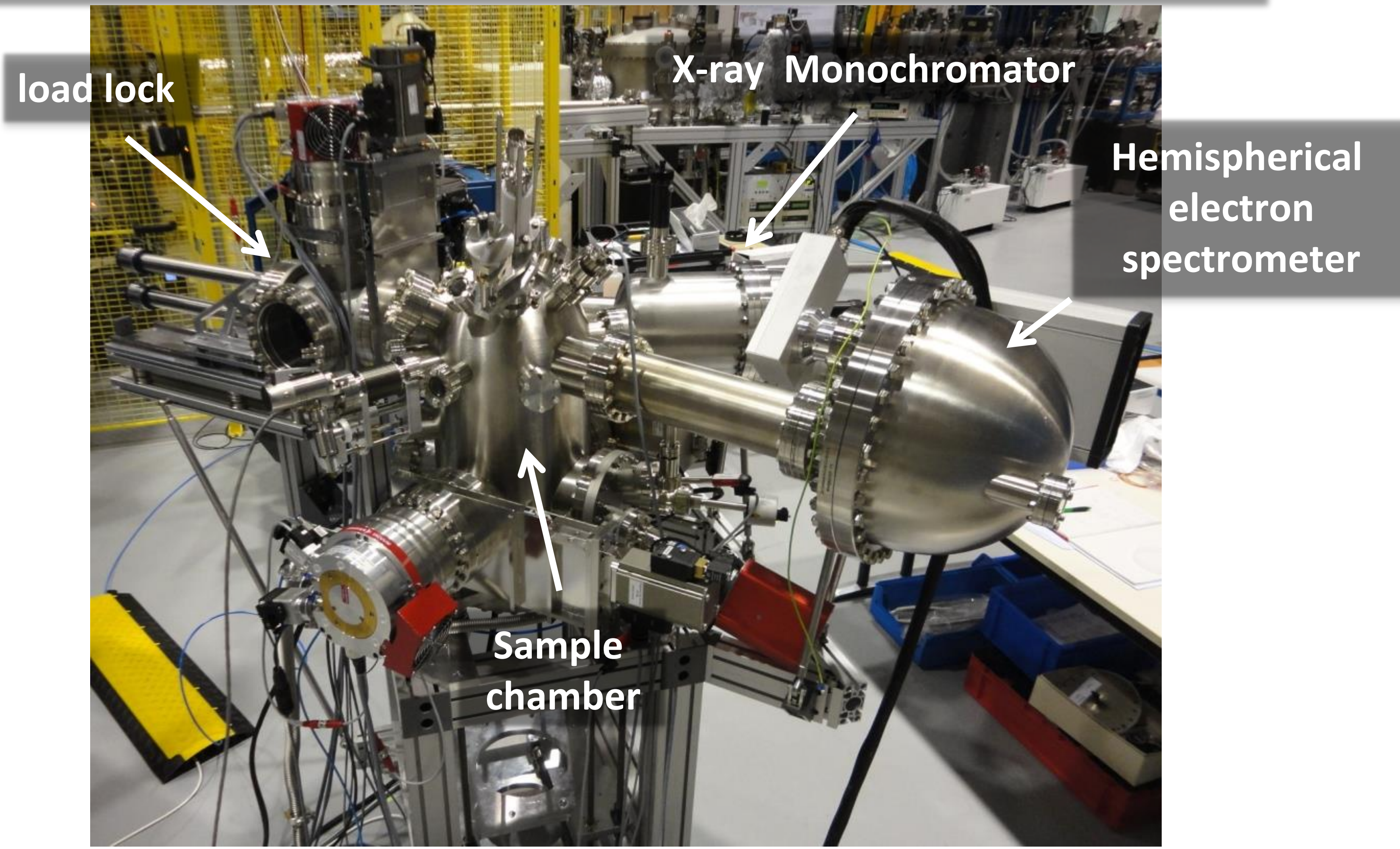
Physisorption → removed by vacuum

Chemisorption → removed only at high temperature in vacuum

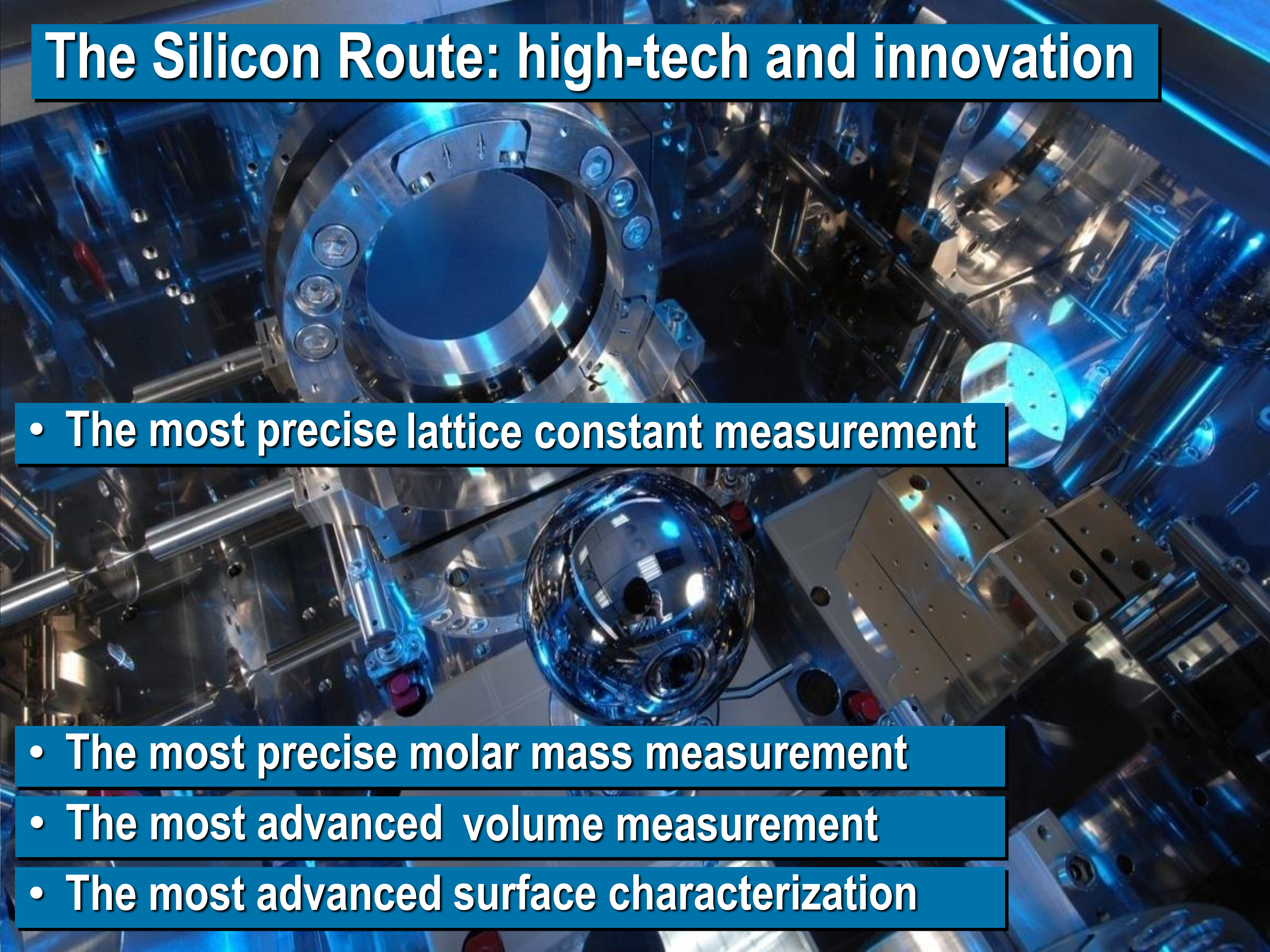
- water
- deconex OP162
- alcohol

surface characterization

Spectroscopy of surface layer with XRF and XPS

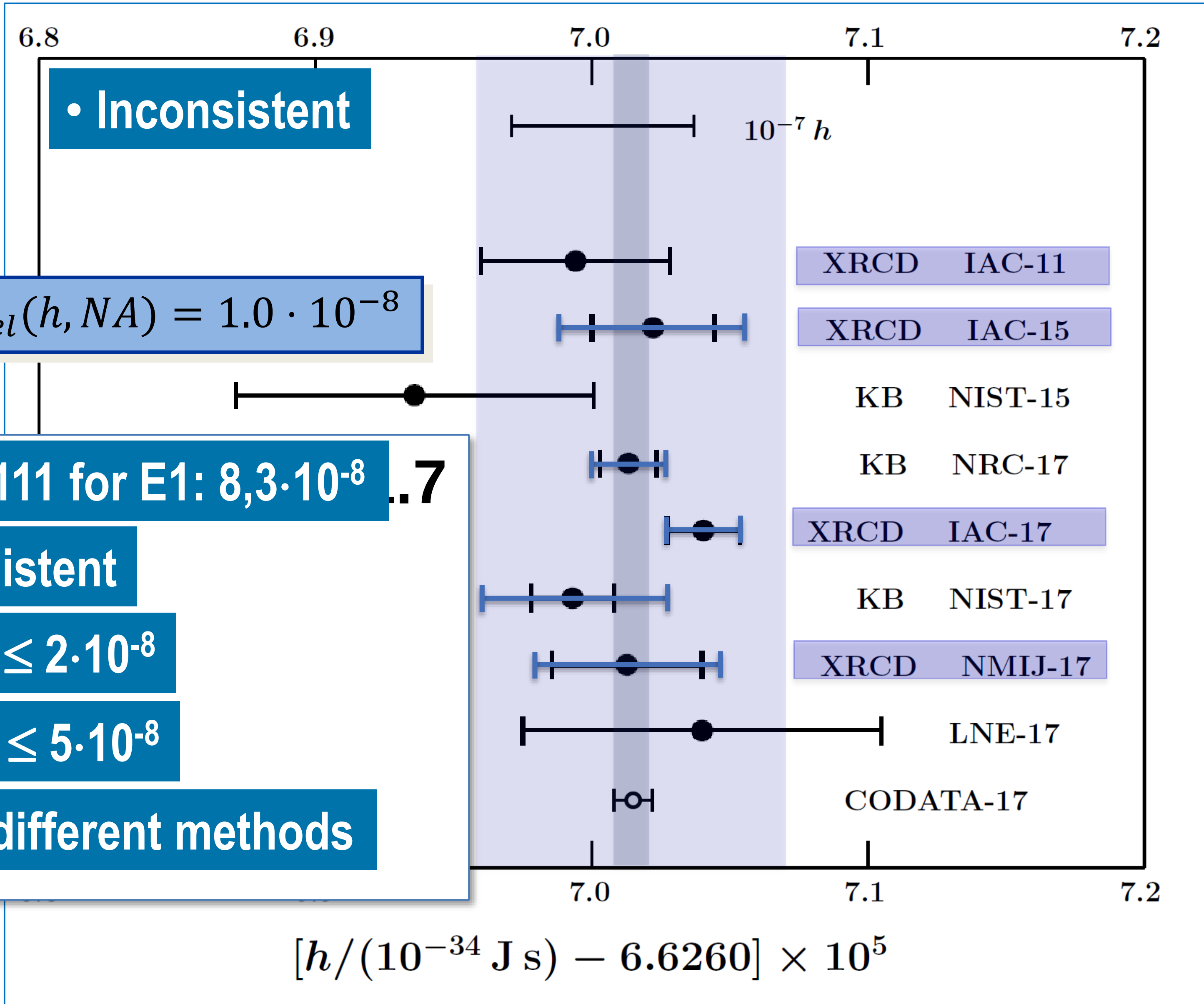


The Silicon Route: high-tech and innovation



- The most precise lattice constant measurement
- The most precise molar mass measurement
- The most advanced volume measurement
- The most advanced surface characterization

Revised International System of Units



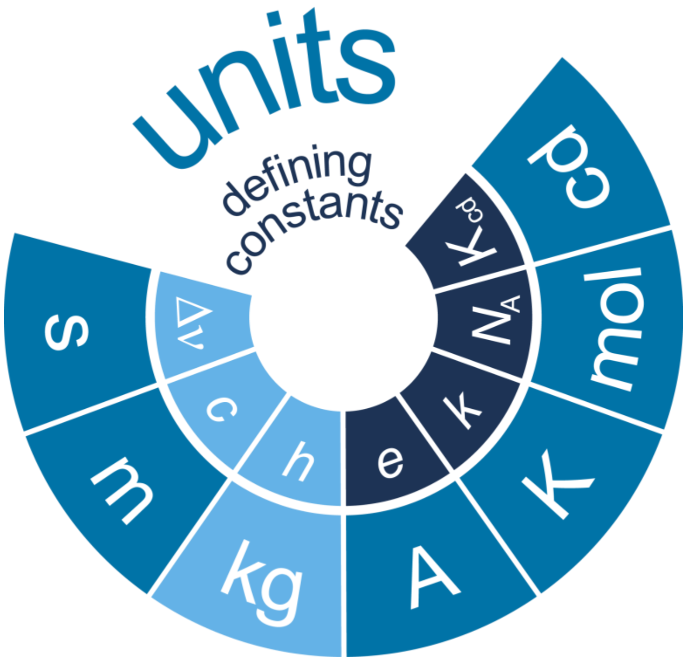
- Inconsistent

$u_{rel}(h, NA) = 1.0 \cdot 10^{-8}$

OIML R111 for E1: 8,3·10^{-8}

- Consistent
- Two: ≤ 2·10^{-8}
- Five: ≤ 5·10^{-8}
- Two different methods

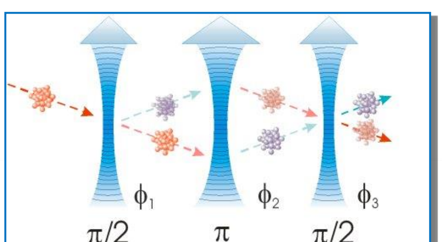
Revised International System of Units



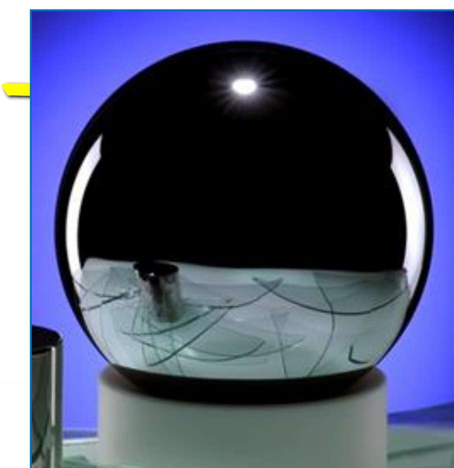
A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe...)
  - Key comparisons: safer, less correlation
  - Atomic masses

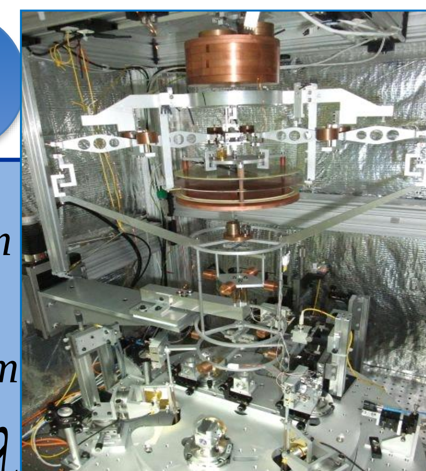
"De Broglie"



"Photon recoil"

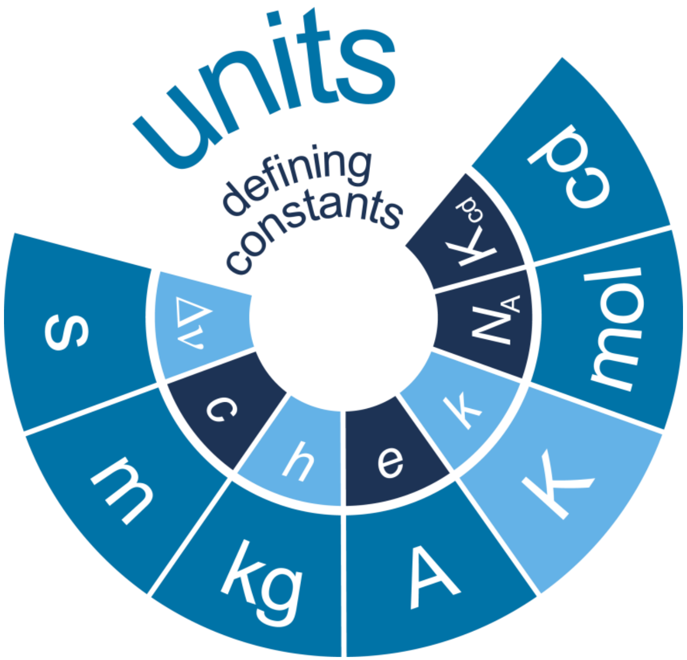


"Silicon crystal"



"Watt balance"

Revised International System of Units

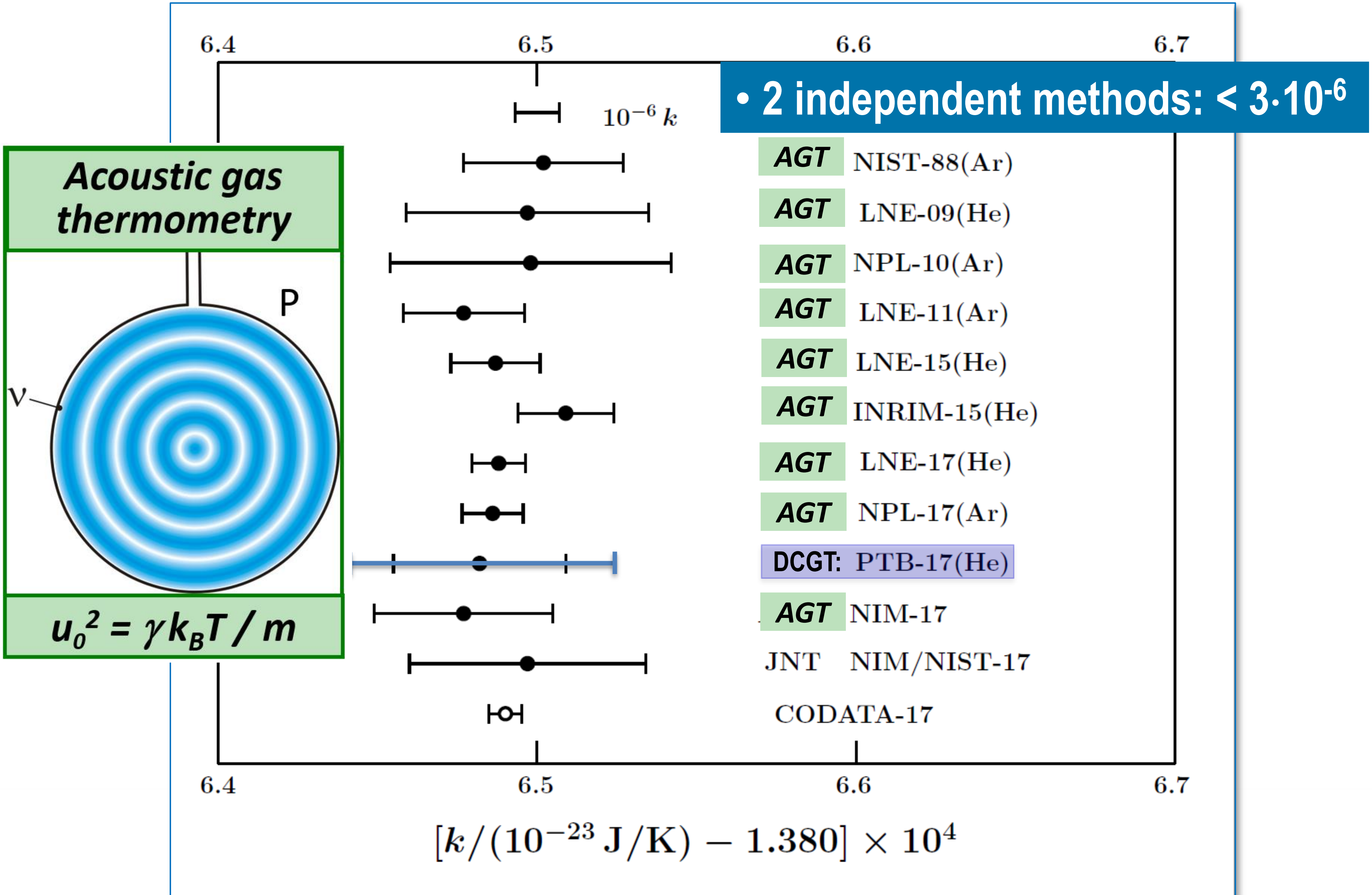


$$E = \frac{1}{2} k \ T$$

A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Throughout the entire scale
  - Acoustic gas thermometry
  - Dielectric constant gas thermometry
  - Doppler thermometry
  - Noise thermometry
  - Radiation thermometry

Revised International System of Units

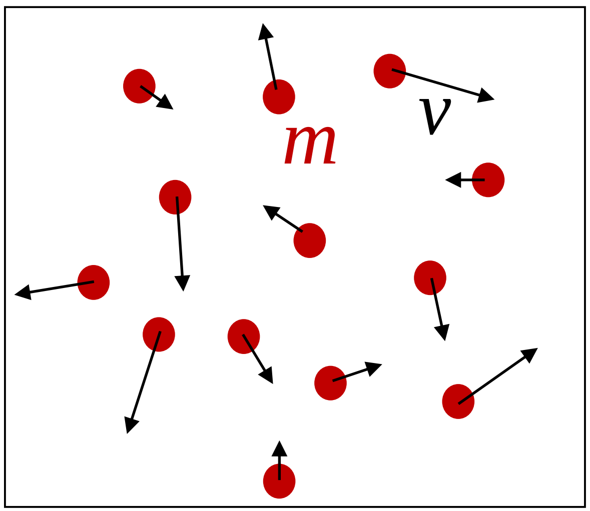


DCGT: Dielectric constant gas thermometry

$$\overline{E}_{kin} = \frac{m}{2}\overline{v}^2 = \frac{3}{2}k_B T$$

$$E = \frac{1}{2}k_B T$$

per degree of freedom



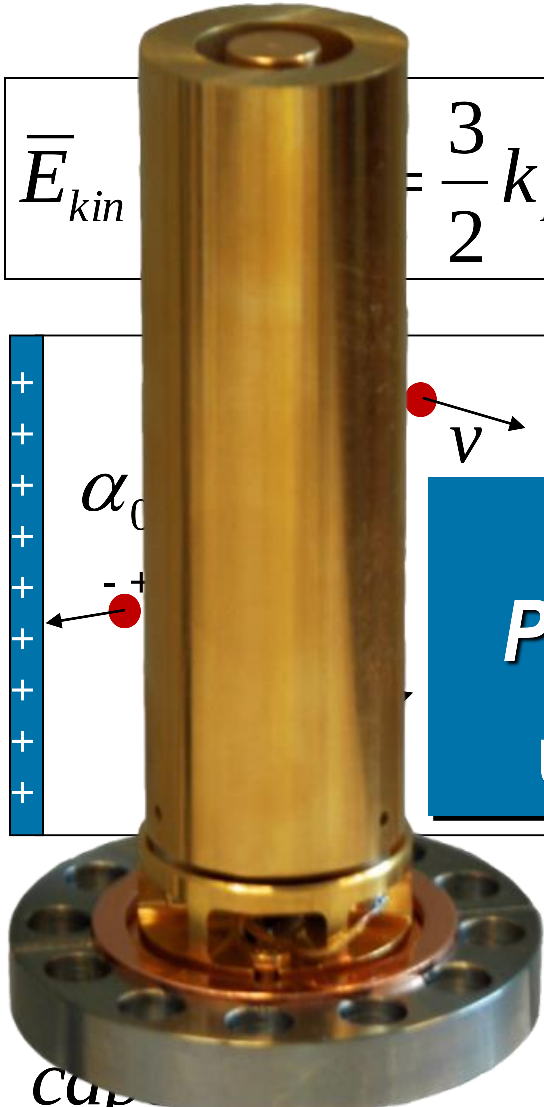
k_B : conversion factor

$volume : V$

$pressure : P$

...how to measure?

DCGT: Dielectric constant gas thermometry



challenge:

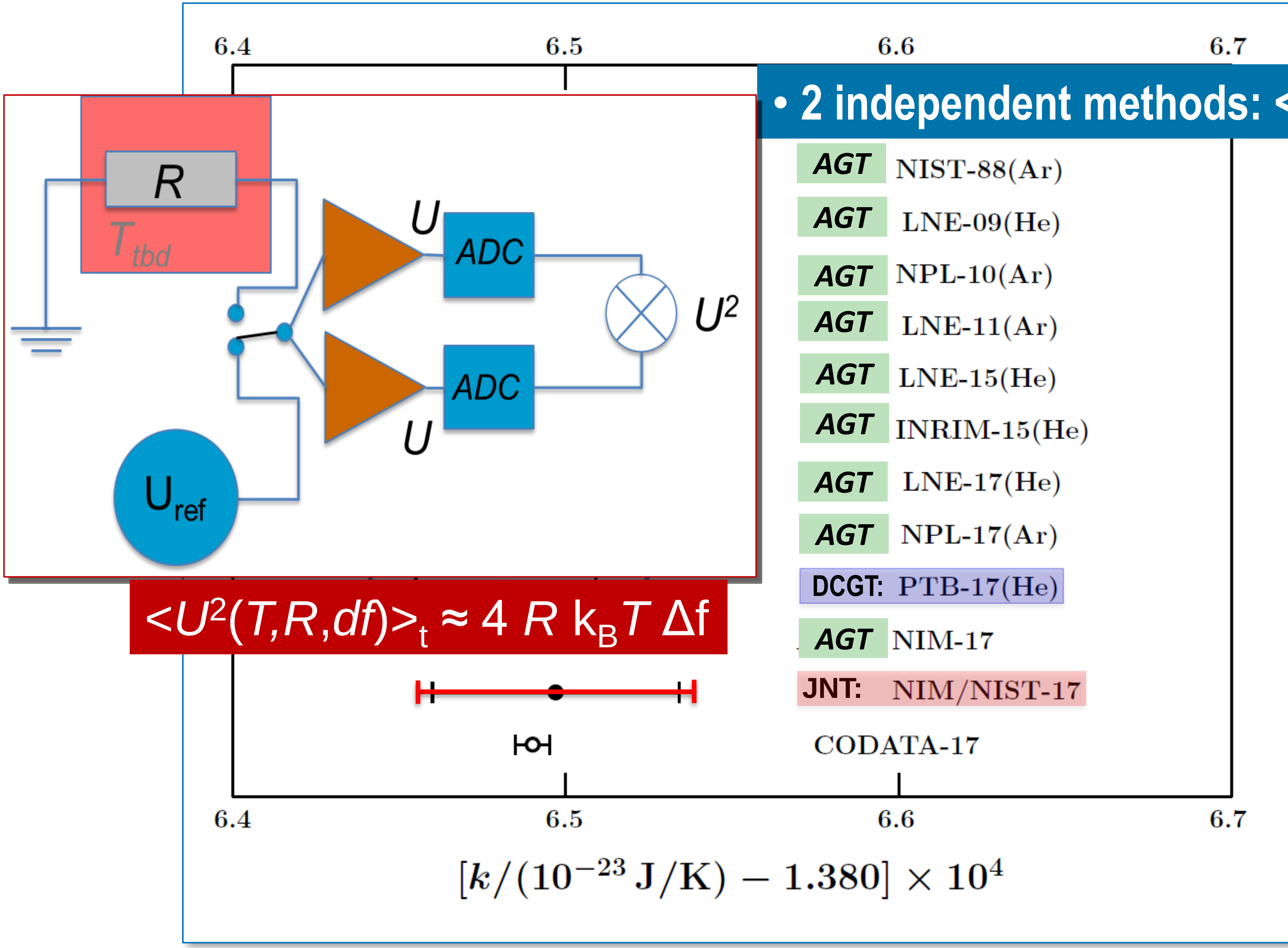
***P* up to 7 MPa**

$u_{rel}(p) \sim 10^{-6}$

Revised International System of Units

PTB

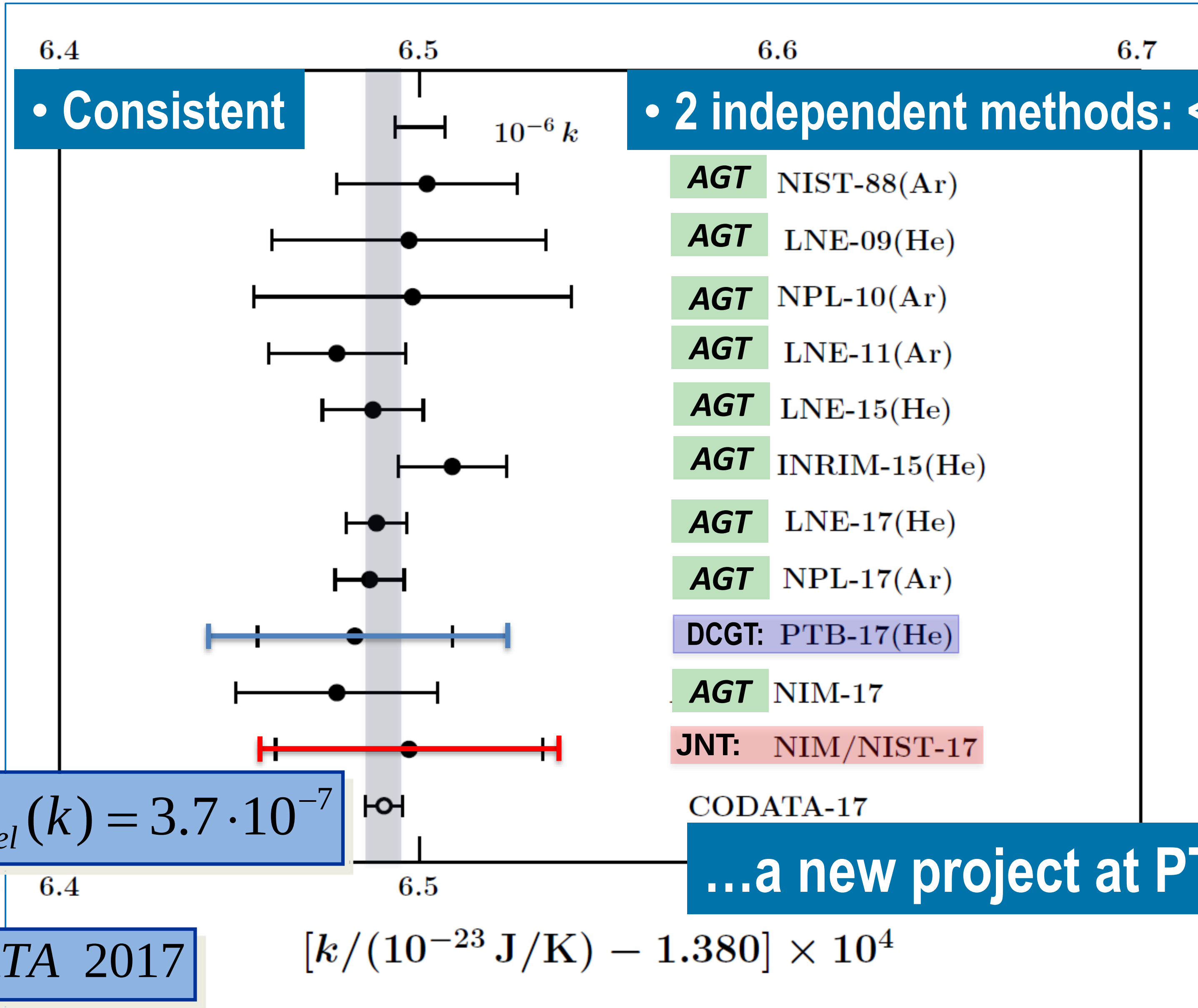
- 2 independent methods: $< 3\cdot10^{-6}$



$$\langle U^2(T,R,df)\rangle_t \approx 4\, R\, k_B T\, \Delta f$$

Revised International System of Units

- Consistent
- 2 independent methods: < $3 \cdot 10^{-6}$



$$u_{rel}(k) = 3.7 \cdot 10^{-7}$$

CODATA 2017

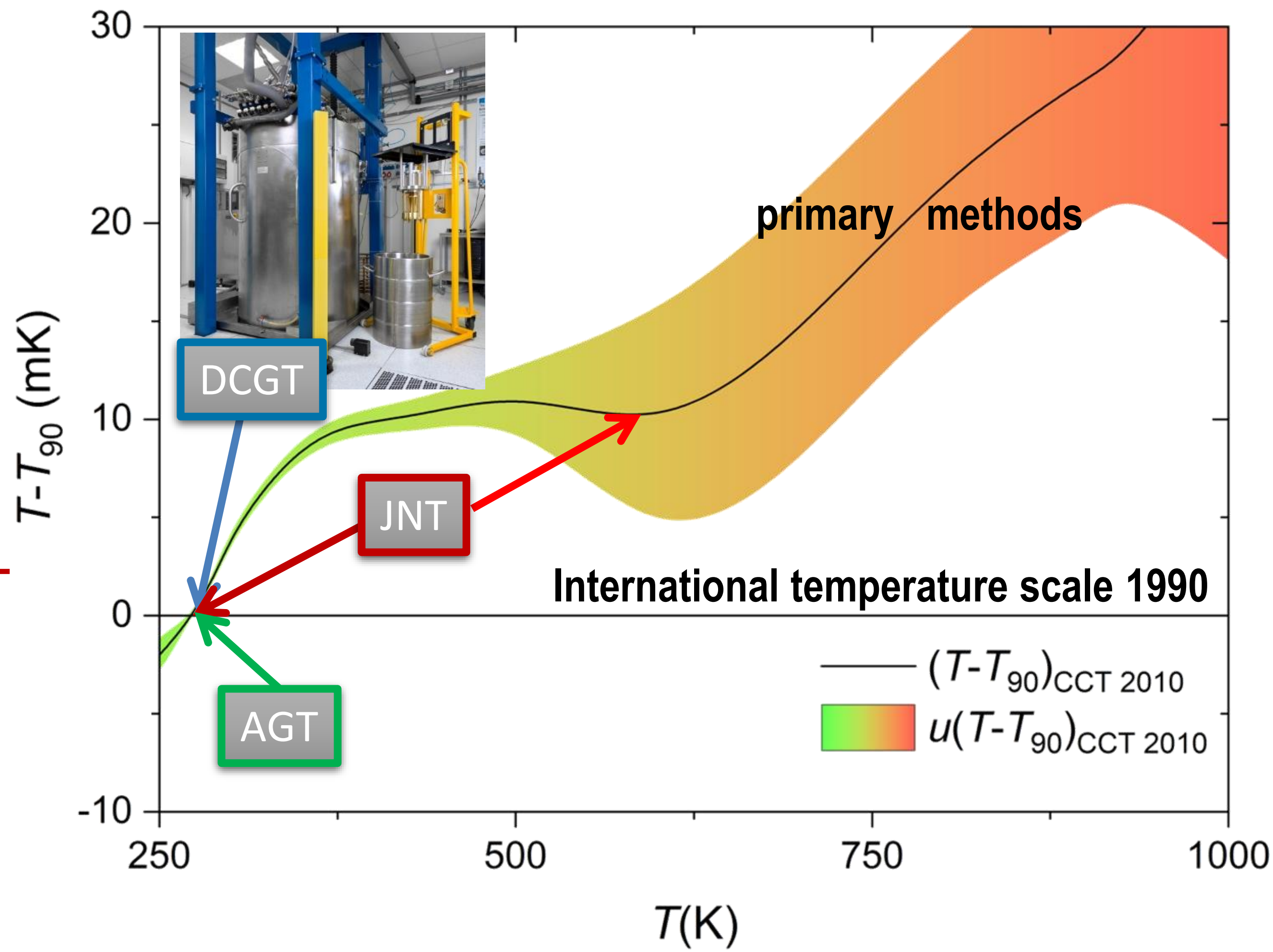
…a new project at PTB

JNT: Johnson-Noise Thermometry

…a new project at PTB

Phase 1 (start in 2021):
Tests of the novel Johnson-Noise-Thermometer (JNT) around 273 K

Phase 3 (after successful tests):
Measure T-T_{90} via JNT above 600K up to 1000 K → Solve large discrepancies and reduce uncertainty significantly

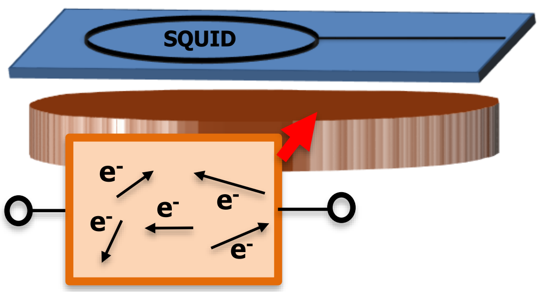


JNT: Johnson-Noise Thermometry

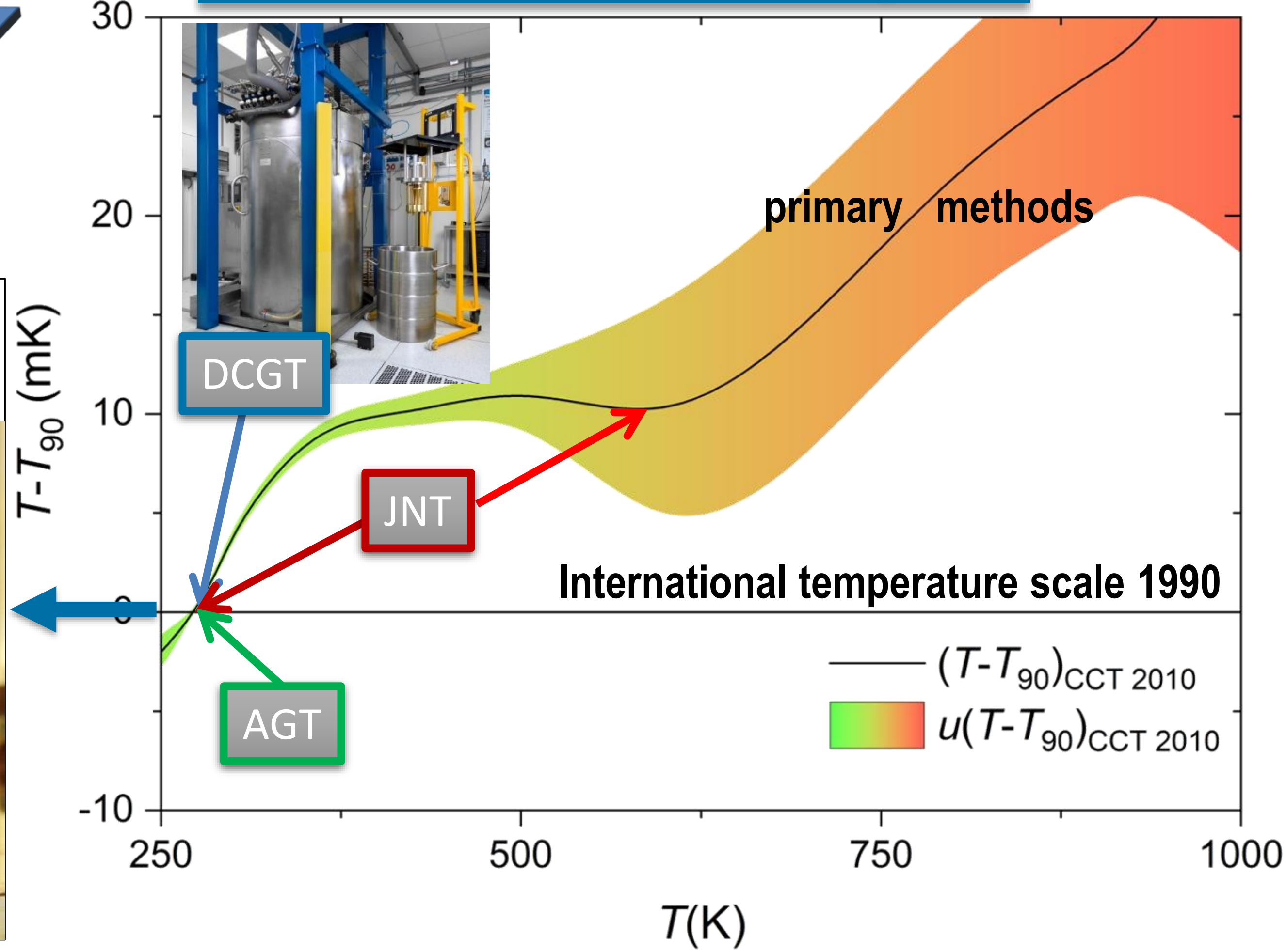
Magnetic Field-Fluctuation-Thermometer (pMFFT)

TB

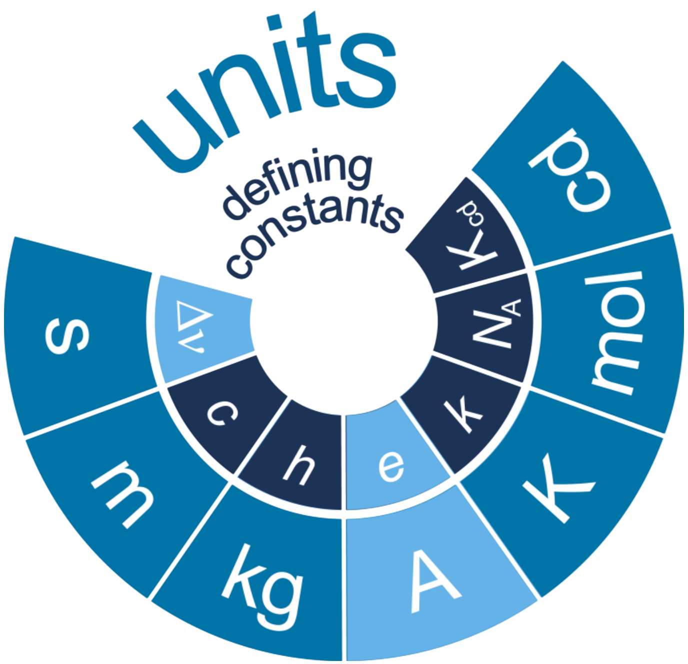
Vision: Realize thermodynamic temperature scale from 1 mK to 1000 K via noise thermometry



C. Ständer, A. Fleischmann, S. Kempf, C. Enss
Universität Heidelberg



Revised International System of Units



$$R_K = \frac{h}{e^2} \approx 25\,813\ \Omega \Leftrightarrow \sout{R_{K-90}}$$

$$K_J = \frac{2e}{h} \approx 483\,598\ GHz/V \Leftrightarrow \sout{K_{J-90}}$$

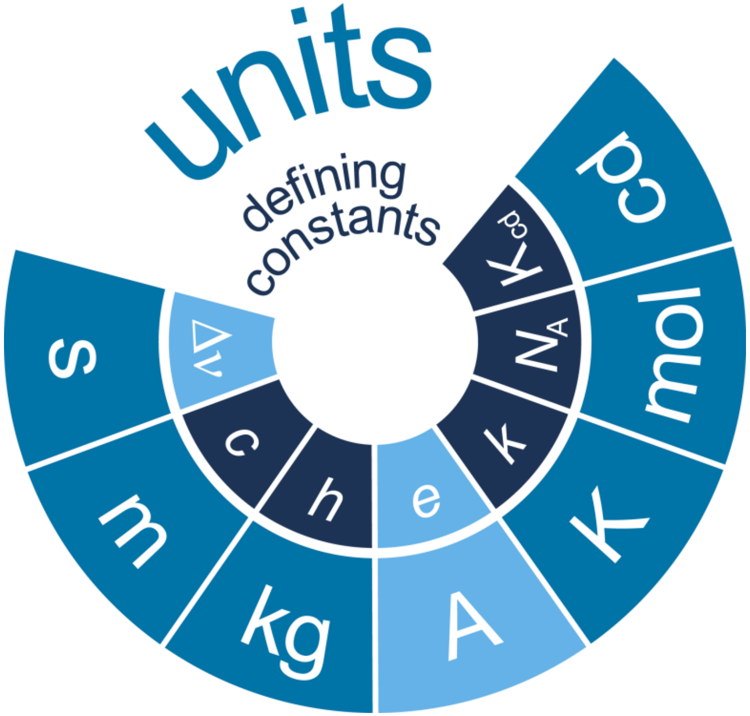
A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Throughout the entire scale
- Electrical units are back in the SI

$$R_K/R_{K-90} - 1 = 1.78 \cdot 10^{-8}$$

$$K_J/K_{J-90} - 1 = -1.06 \cdot 10^{-7}$$

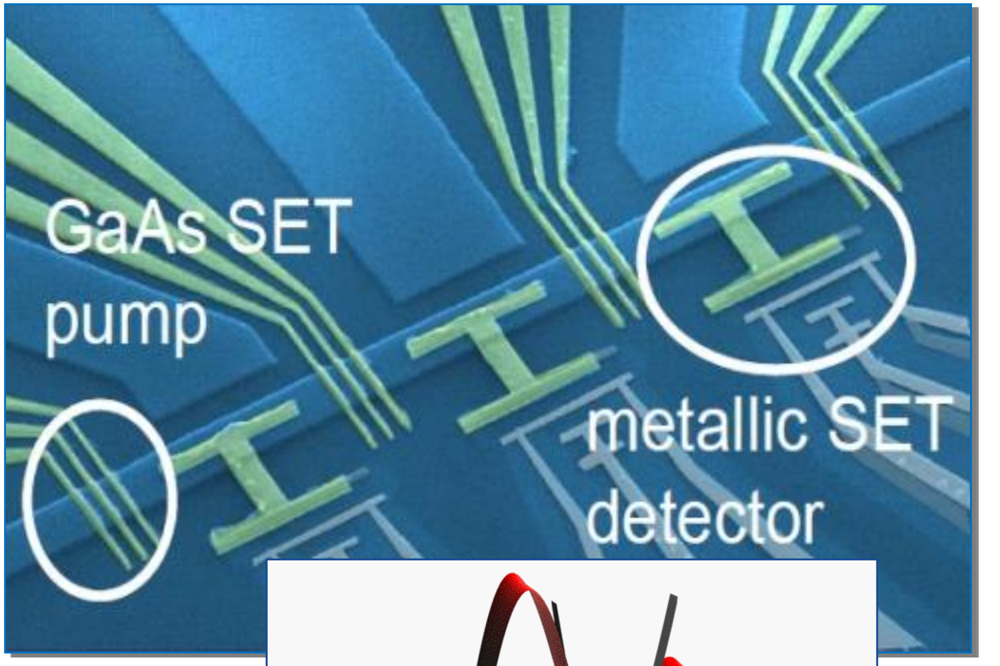
Defining Constants Creating the Units

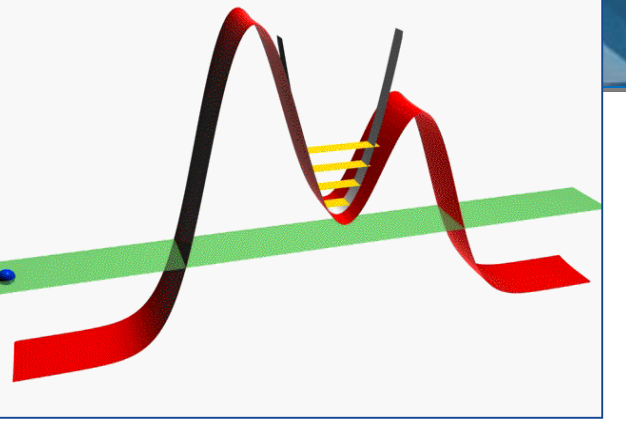


$$I = \langle n \rangle \cdot e \cdot f$$

Count the flow of electrons in a second

$e = 1.602\,176\,634 \cdot 10^{-19}$ C

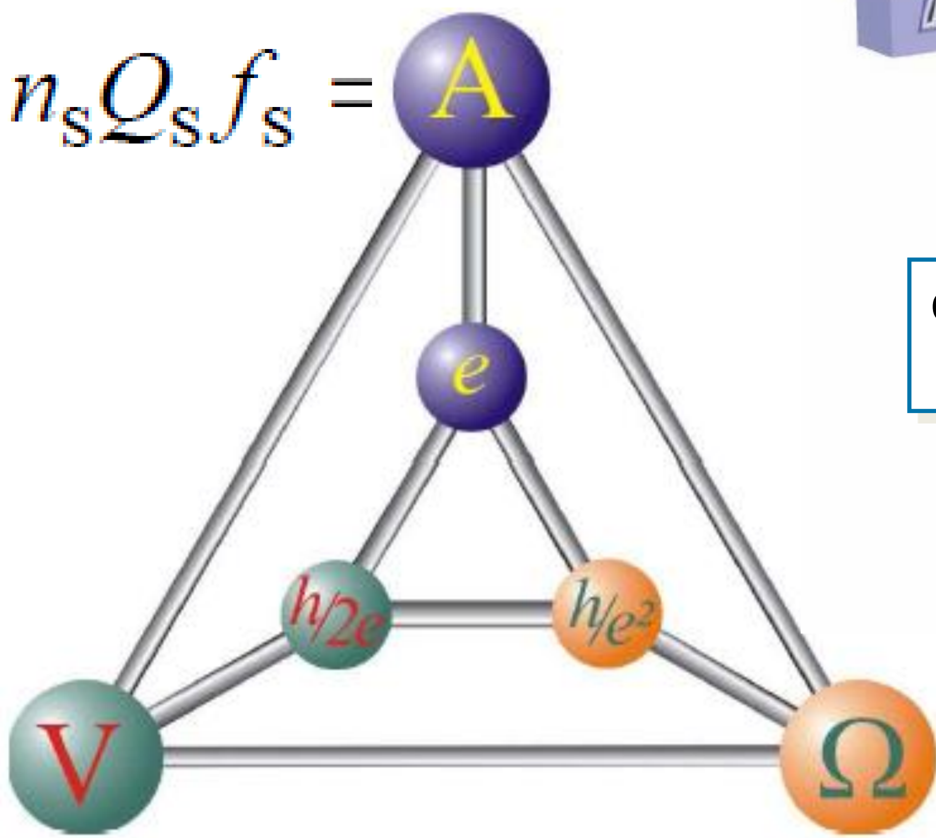


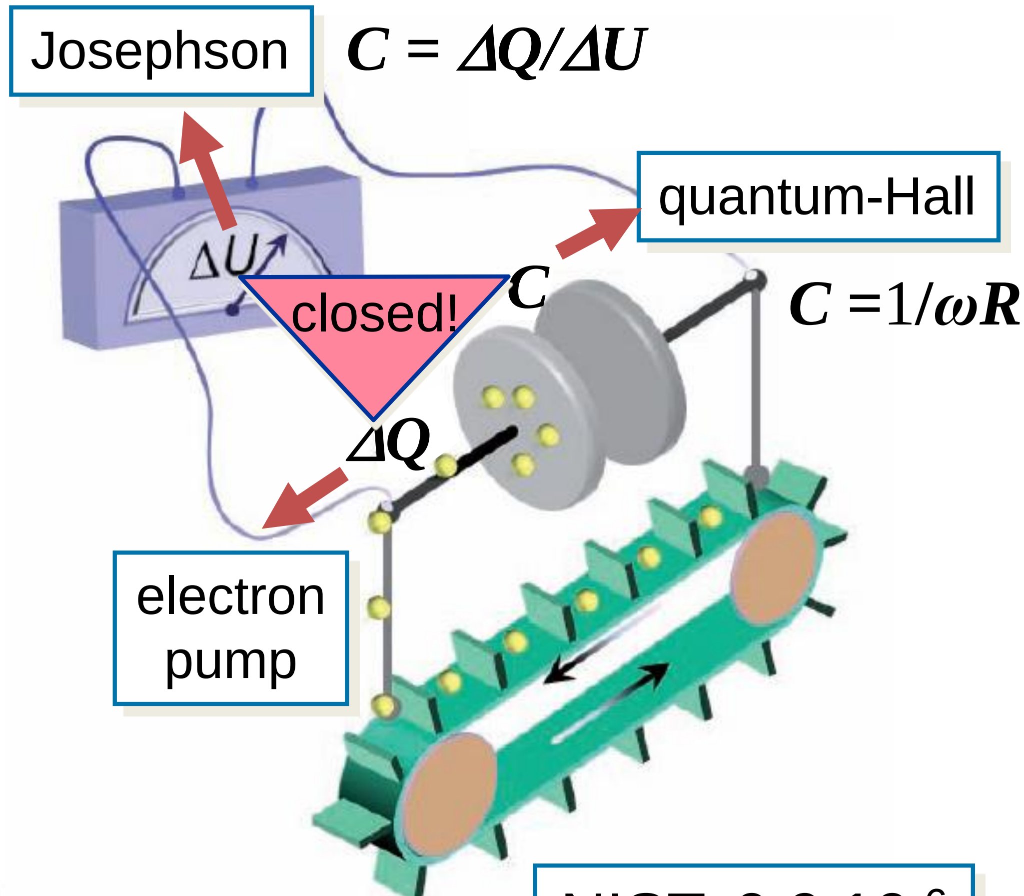


The Quantum Metrological Triangle

$$K_J R_K Q_S = 2$$

$$n_S Q_S f_S =$$





NIST: $0.9 \cdot 10^{-6}$

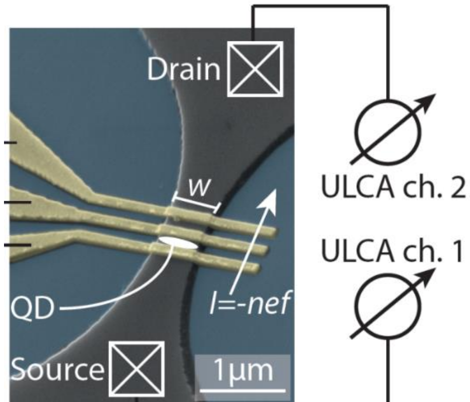
PTB 2015: $0.16 \cdot 10^{-6}$

F. Stein et al., APL 107(10), 103501, 2015.

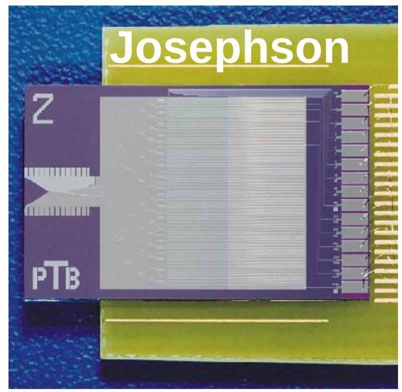
Quantum Frontiers Quantum Devices

World-class performance!

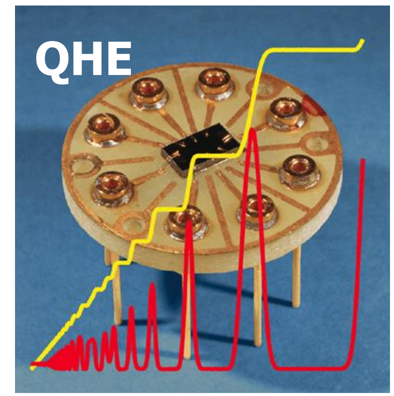
Single Electron Transistor



Josephson Device



Quantum Hall Device



world leading | world leading | world leading

$$\left(\frac{h}{e^2}\right)_{QHE}\left(\frac{2e}{h}\right)_J (e)_{SET} \stackrel{?}{=} 2$$

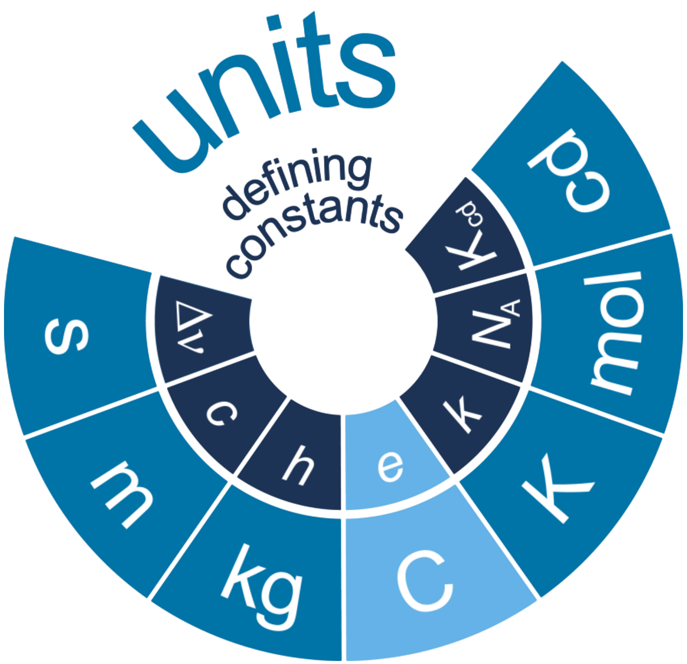
challenge: 10^{-8}

Are these quantum effects precisely quantized?

Is our understanding of the quantum effects correct?

Revised International System of Units

PTB



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- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Throughout the entire scale
- Electrical units are back in the SI
- Base units are only a convention
- Innovation: research & industry

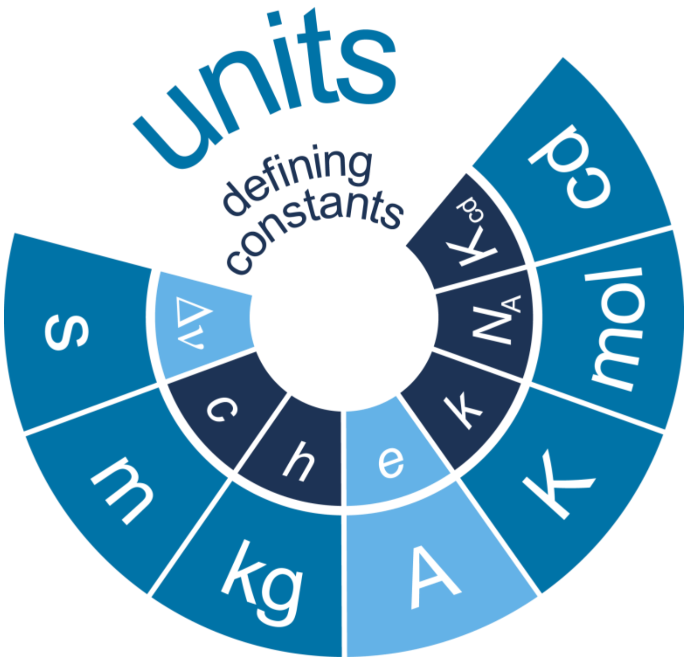
$$R_K = \frac{h}{e^2} \approx 25\,813\,\Omega \Leftrightarrow R_{K-90}$$

$$K_J = \frac{2e}{h} \approx 483\,598\ GHz/V \Leftrightarrow K_{J-90}$$

- Commercial Watt balance
- Johnson noise thermometry
- Single Electron Tunneling devices
- QH in graphene, QHE in topological insulators

Revised International System of Units

Tremendous benefits:



a "huge" change…
but "no" change!

A concept improved fundamentally!

- Guarantees long-time stability
- A set of "defining constants" establish the units in general
- Different realisations
- Realisation everywhere (Universe…)
- Throughout the entire scale
- Electrical units are back in the SI
- Base units are only a convention
- Innovation: research & industry
- Better experiment → better realization

Ensure continuity, harmonization, stability

SI International System of Units

THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

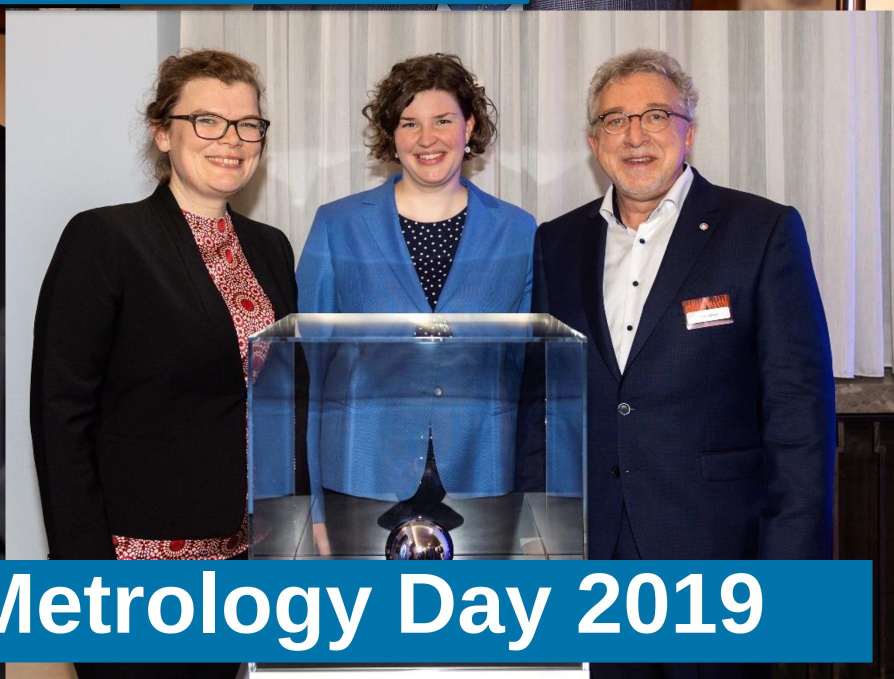
26th CGPM Meeting, Versailles, 16.11.18

A historic event!

World metrology day celebration

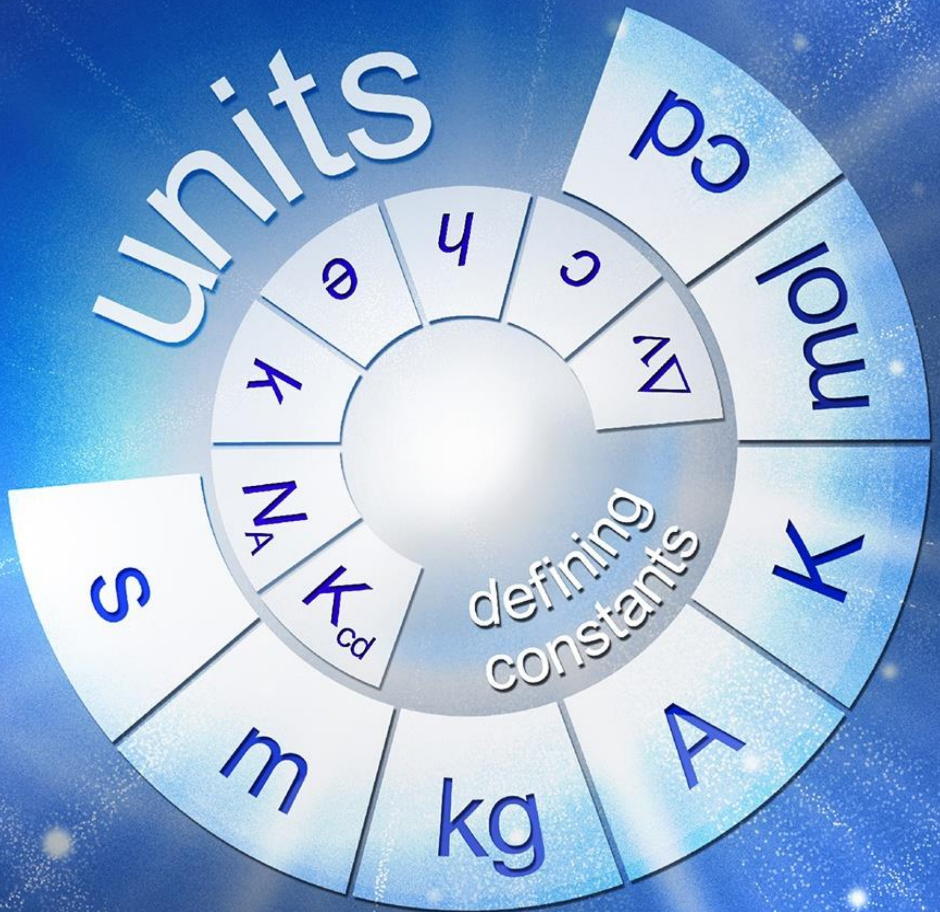
Deutsches Museum

PTB



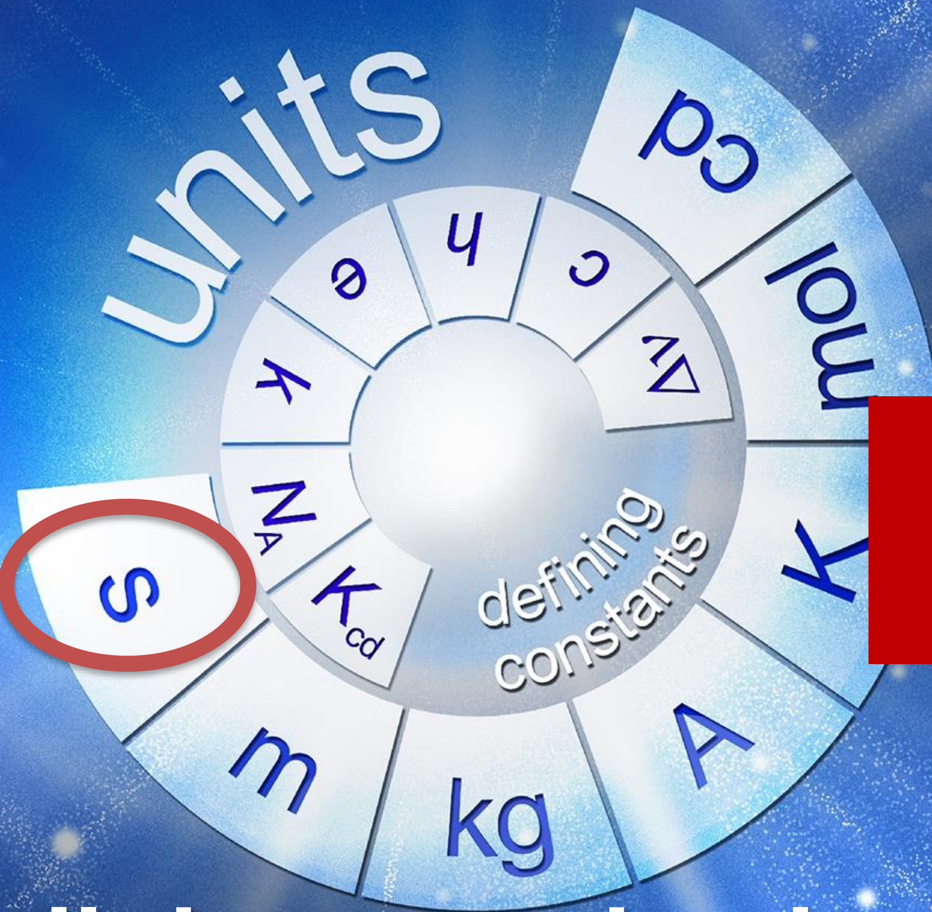
In force since: World Metrology Day 2019

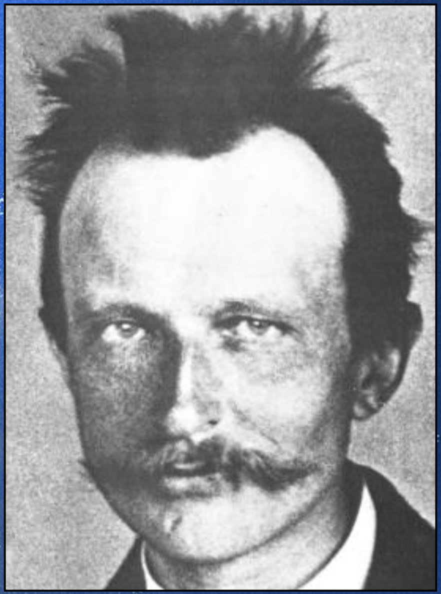
SI International System of Units



…approaching the most abstract definition of units...

SI International System of Units





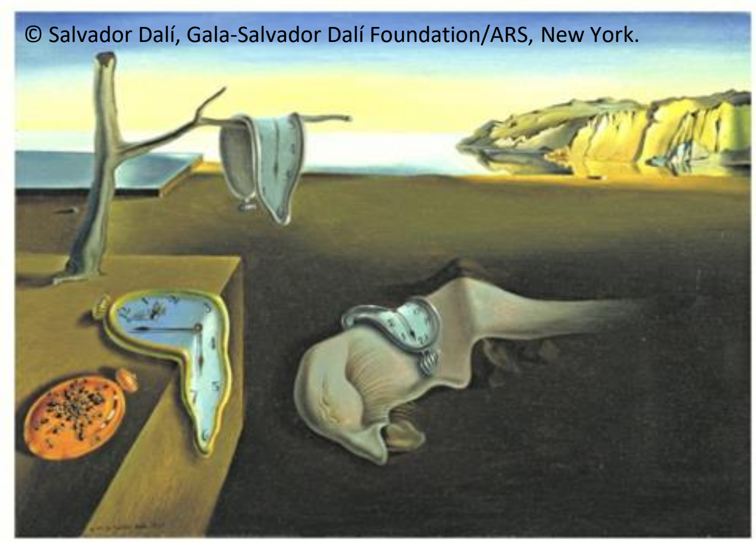
And what about the second?

For all times and cultures Throughout the Universe….

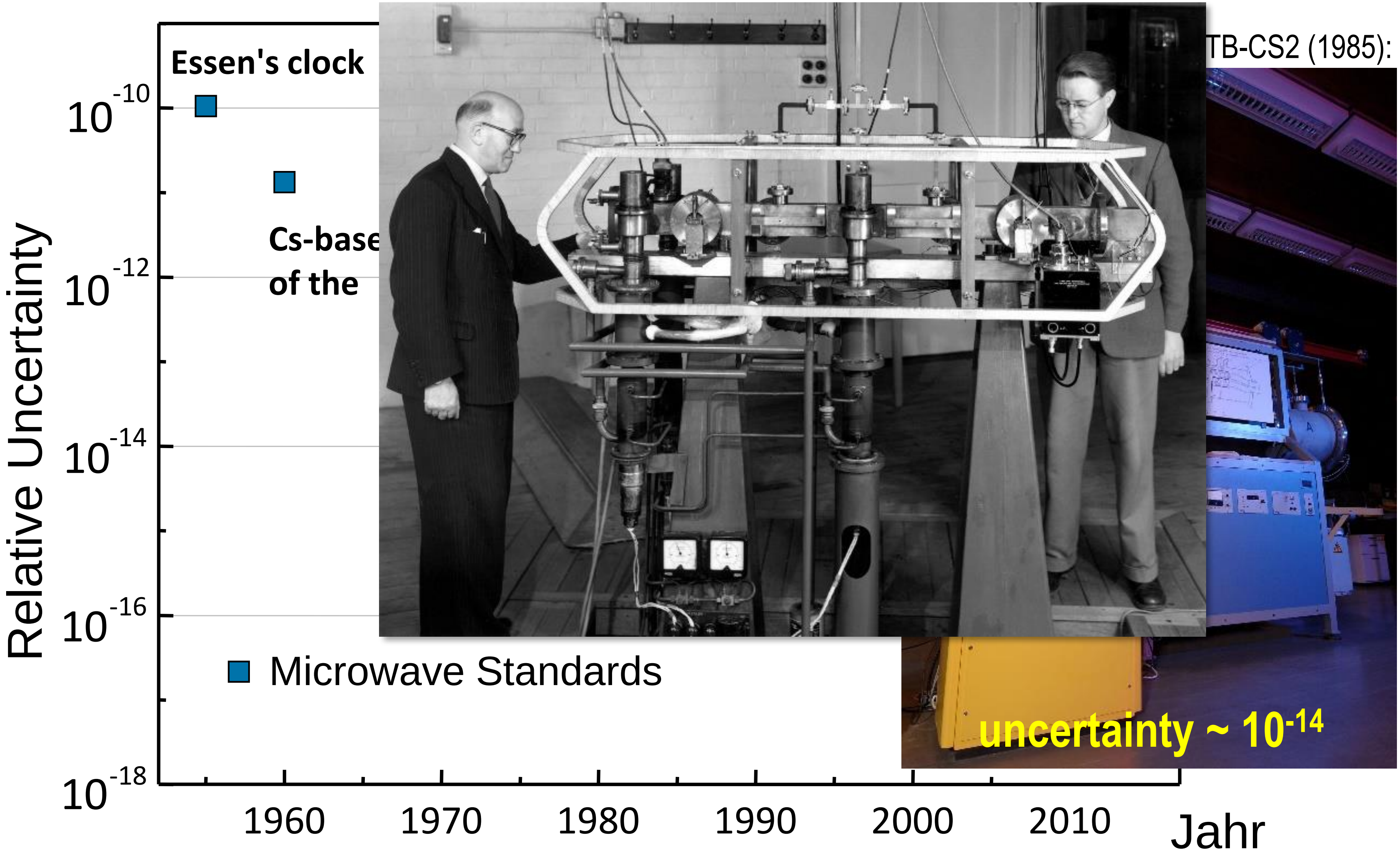
Linking the International System of Units to Fundamental Constants:

Precision Experiments for the Revised SI

1. The international syste
2. Defining constants for t
3. **About the future of time**



About the future of time



The Magneto-Optical Trap (MOT)

→ 3D trapping and cooling

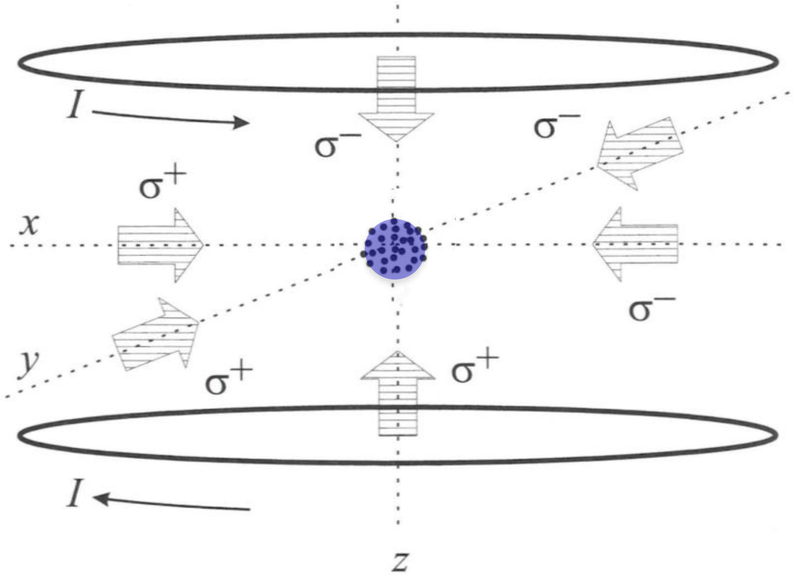


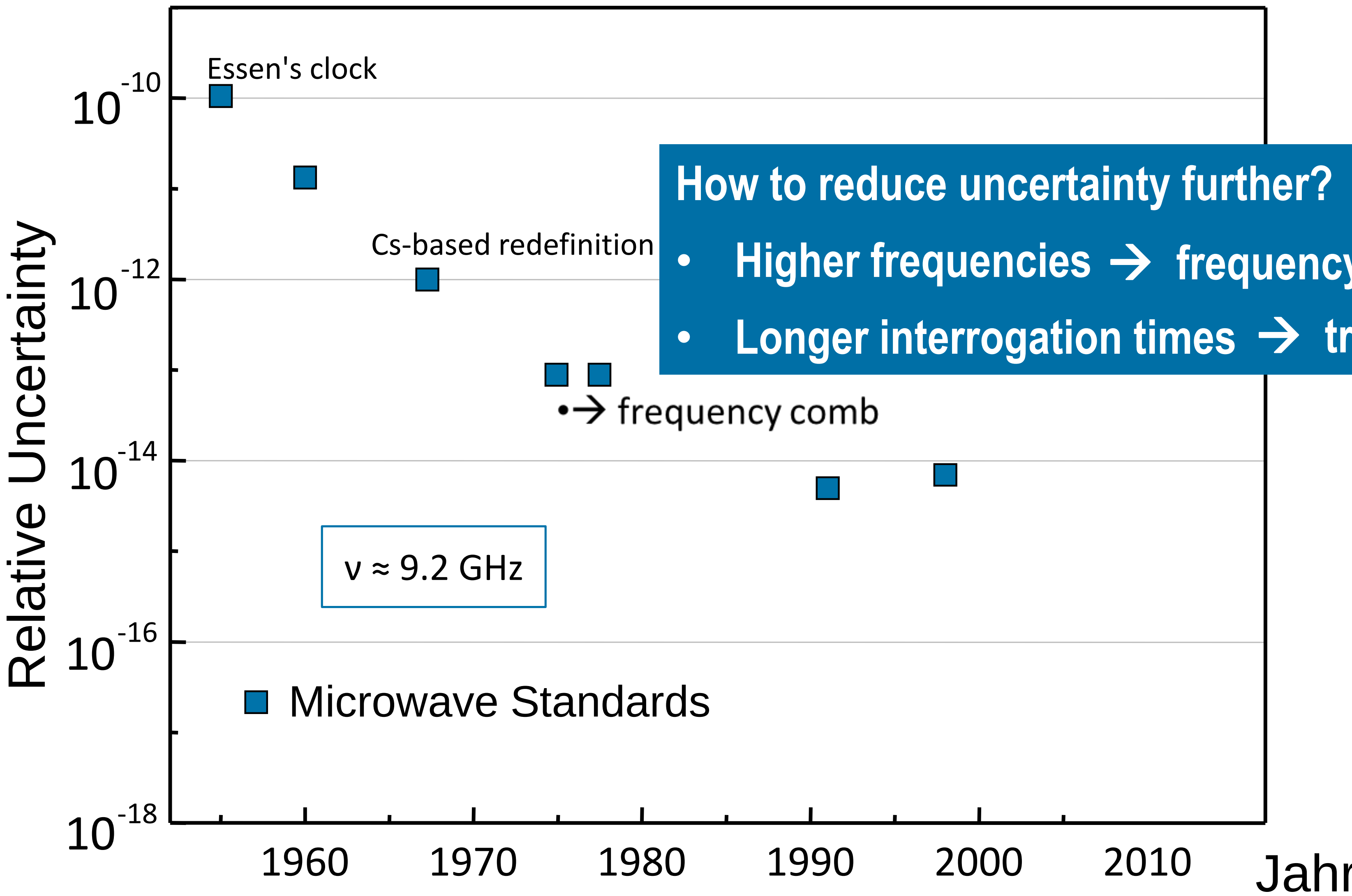
figure from F. Riehle,
Frequency Standards, Wiley-VCH

- 3 orthogonal pairs of counter-propagating laser beams
- a spherical quadrupole magnetic field (pair of anti-Helmholtz coils)

→ harmonic potential for trapping the atoms

→ Atomic fountain clock

About the future of time



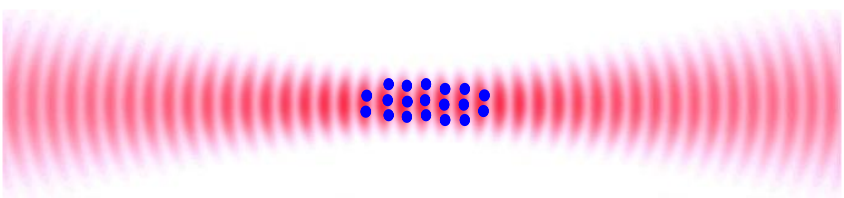
How to reduce uncertainty further?

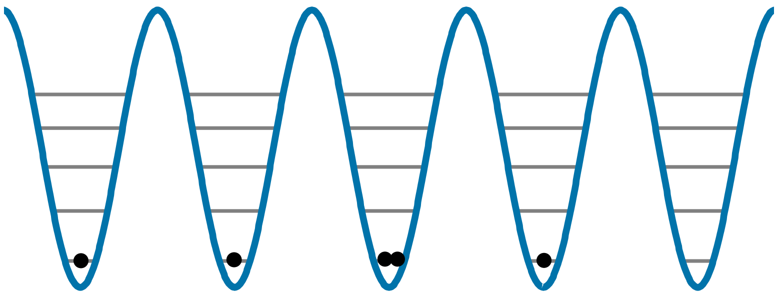
- Higher frequencies → frequency comb
- Longer interrogation times → traps

Traps for clocks

Atom traps

- Large number of atoms (n ~ 10^3 - 10^5)
  → **High stability**
- Optical lattice → **Strong confinement**
- "Magic" Wavelength
  → **Suppress frequency shift of clock transition**





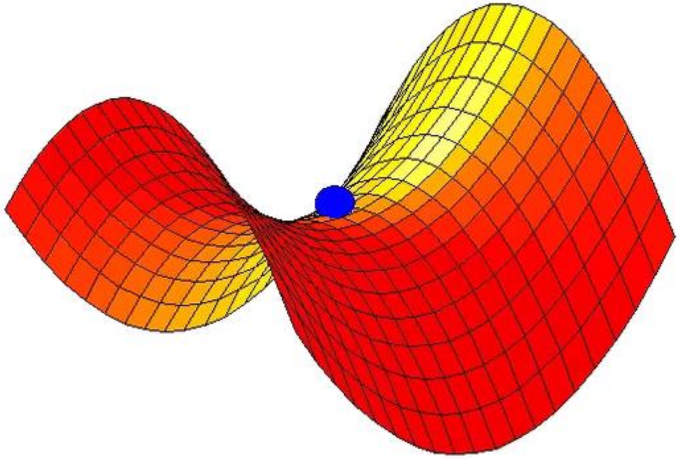
Ion traps

- Uses RF-quadrupole-fields
- trap with electric fields
  → **Charged particles interact strongly with environment**
- large trap depth:
  → **storage times: days/months**

Wolfgang Paul

1913 – 1993

Nobel prize 1989

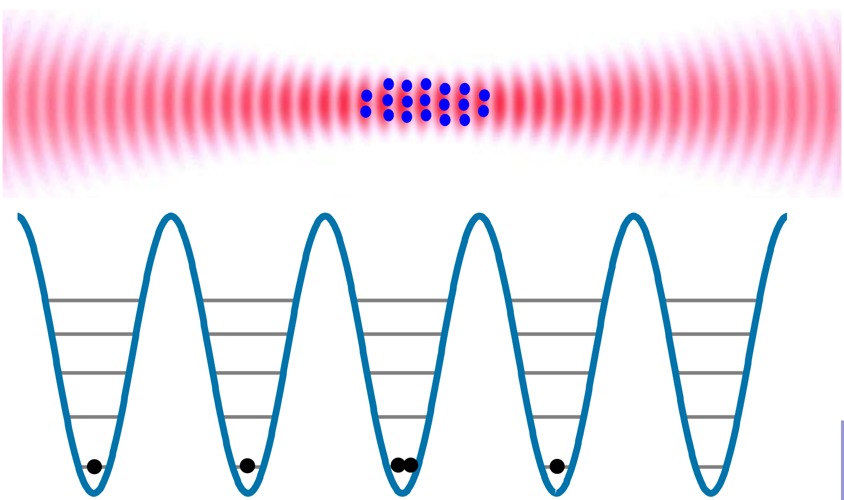


Ponderomotive Potential

Traps for clocks

Atom traps

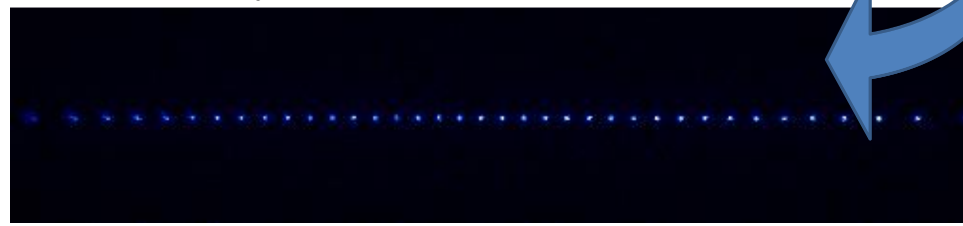
- Large number of atoms (n ~ 10^3 - 10^5)
  → **High stability**
- Optical lattice → **Strong confinement**
- "Magic" Wavelength
  → **Suppress frequency shift of clock transition**



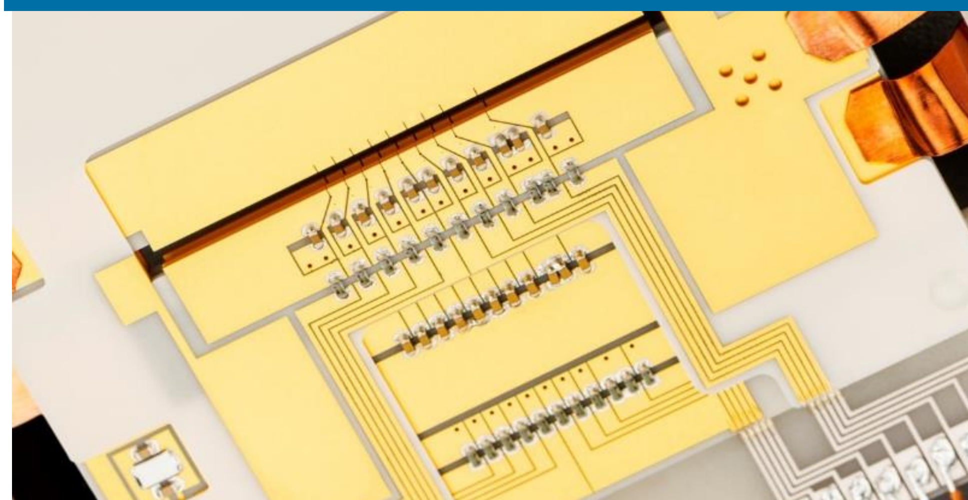
Multi-ion traps

1 Yb^+ ion

Coulomb crystal of 37 Yb^+ ions



Segmented multi-ion traps: >100 ions

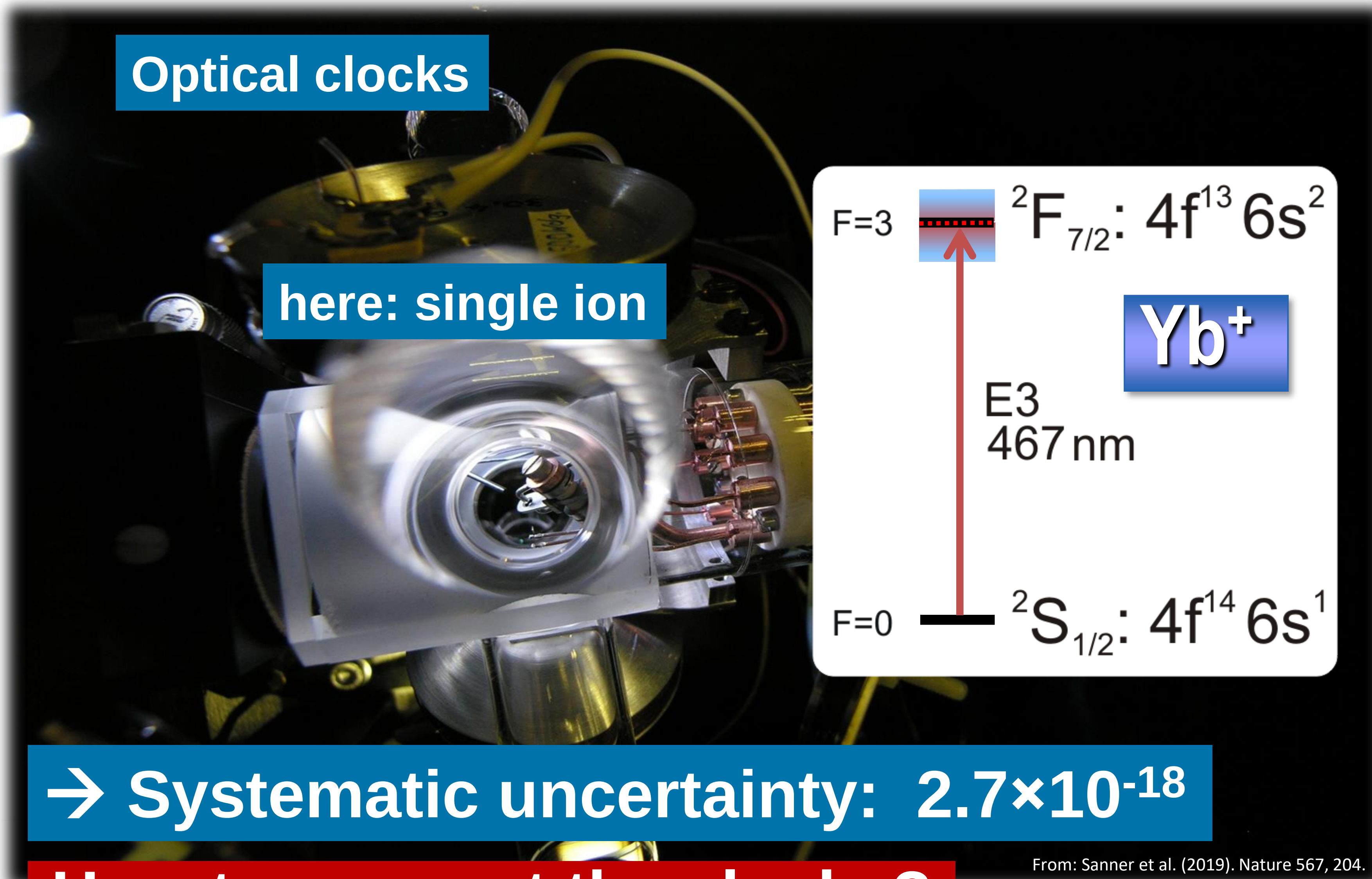


→ Entangled ions in multi-ion traps…

About the future of time at PTB

Optical clocks

here: single ion



→ Systematic uncertainty: 2.7×10^{-18}

From: Sanner et al. (2019). Nature 567, 204.

How to connect the clocks?

About the future of time

Brillouin amplification supports 1×10^{-20} accuracy in optical frequency transfer over 1400 km of underground fibre

Sebastian M. F. Raupach,[1,*] Andreas Koczwara,[1] and Gesine Grosche[1]

[1] *Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany*

(Dated: March 20, 2015)

green: in operation

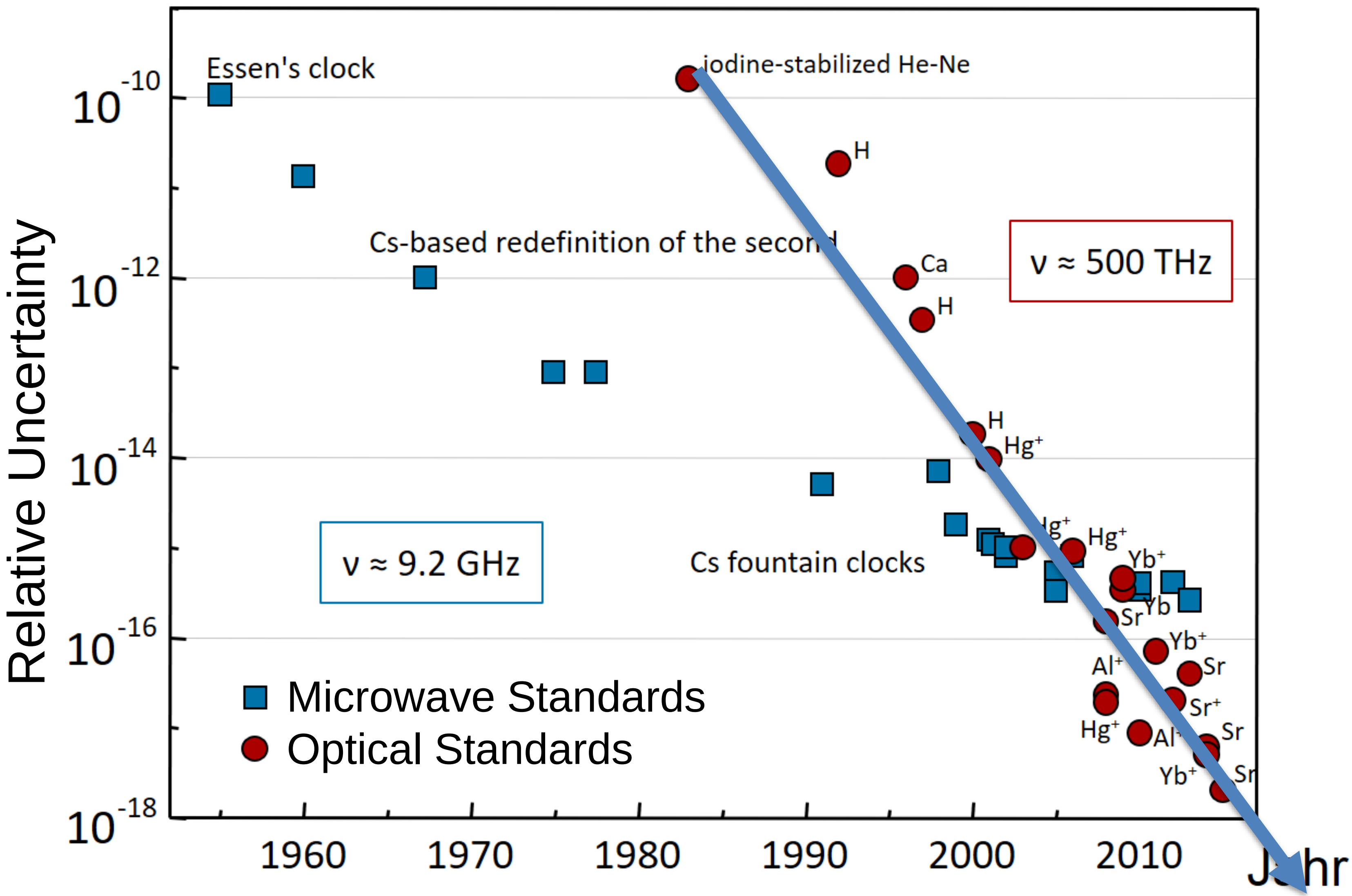
yellow: commissioning

red: planned

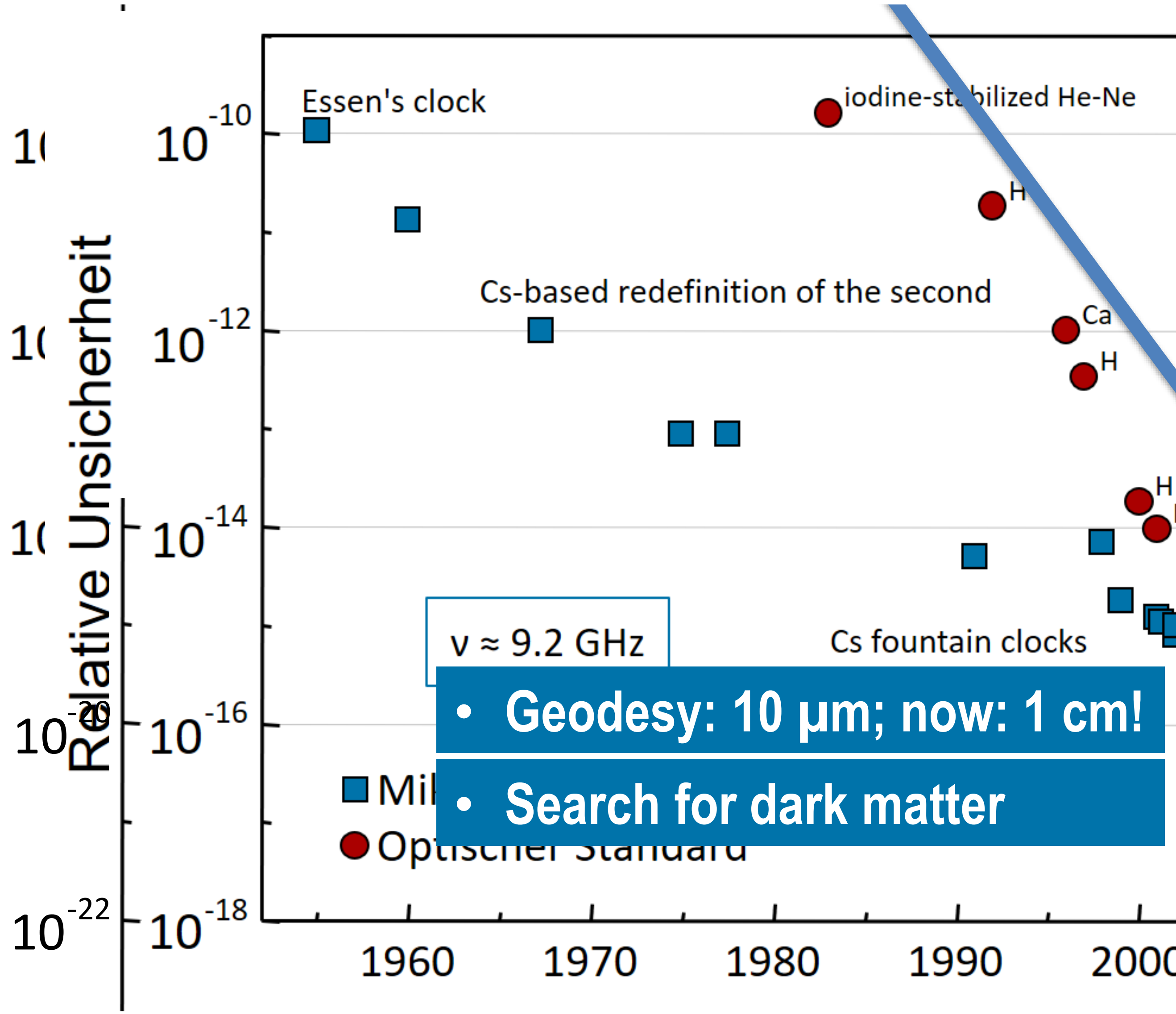
NIST (J. Ye): first laser air link: ~10^{-18} demonstrated!

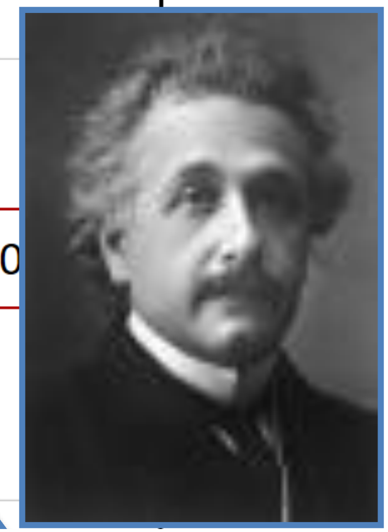
First agreement of two very distant clocks with $4.7 \cdot 10^{-17}$! → world record!

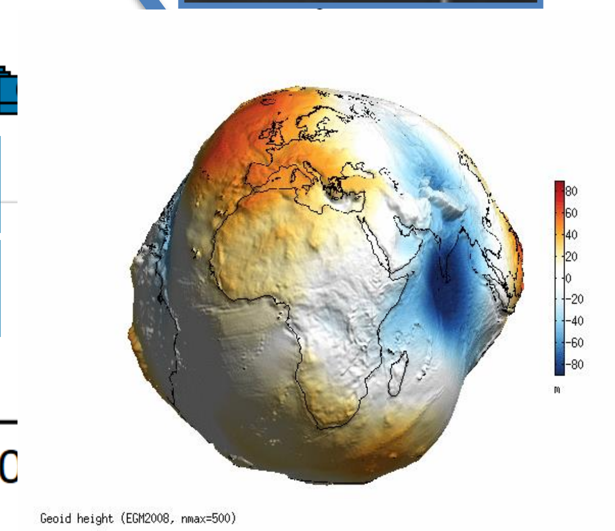
About the future of time



About the future of time



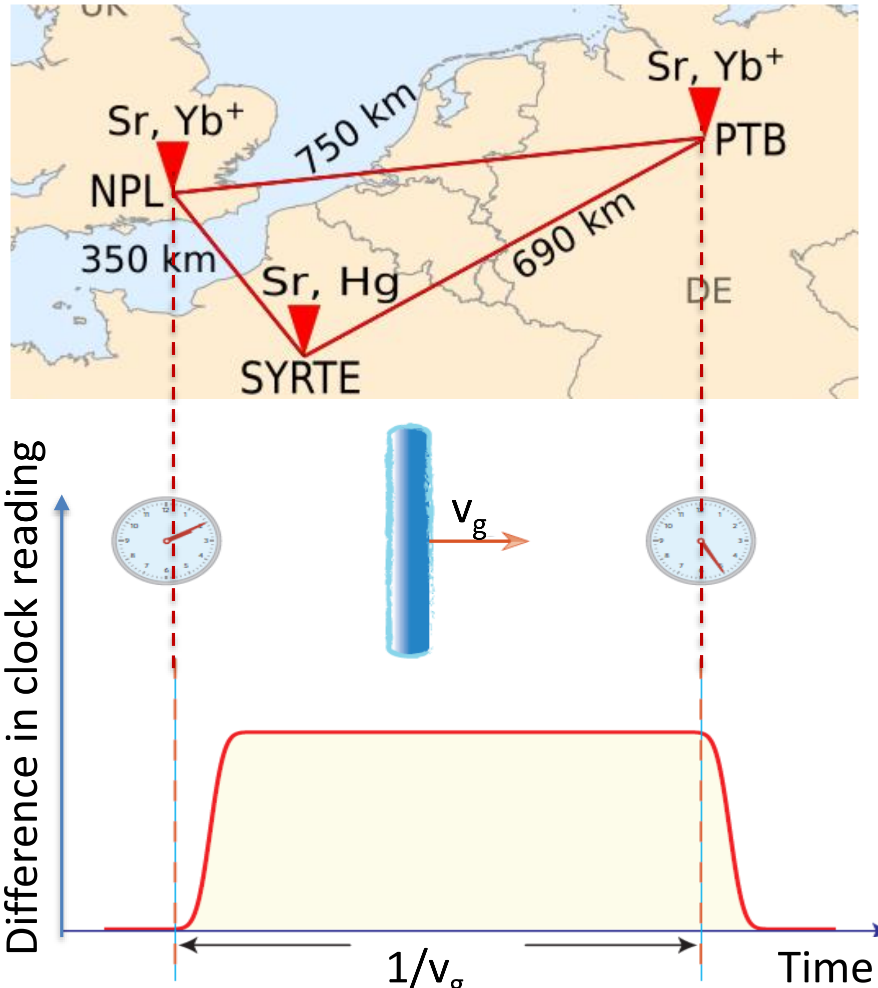




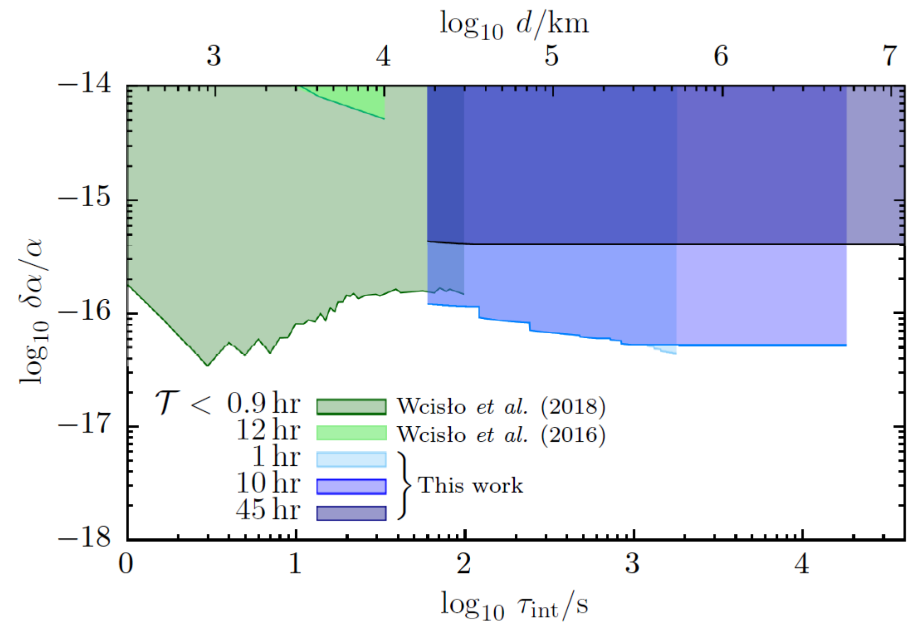
- **Geodesy: 10 µm; now: 1 cm!**
- **Search for dark matter**

About the future of time

- **Search for dark matter**



© Derevianko *et al.* (2014). Nature Physics 10, 933-936.



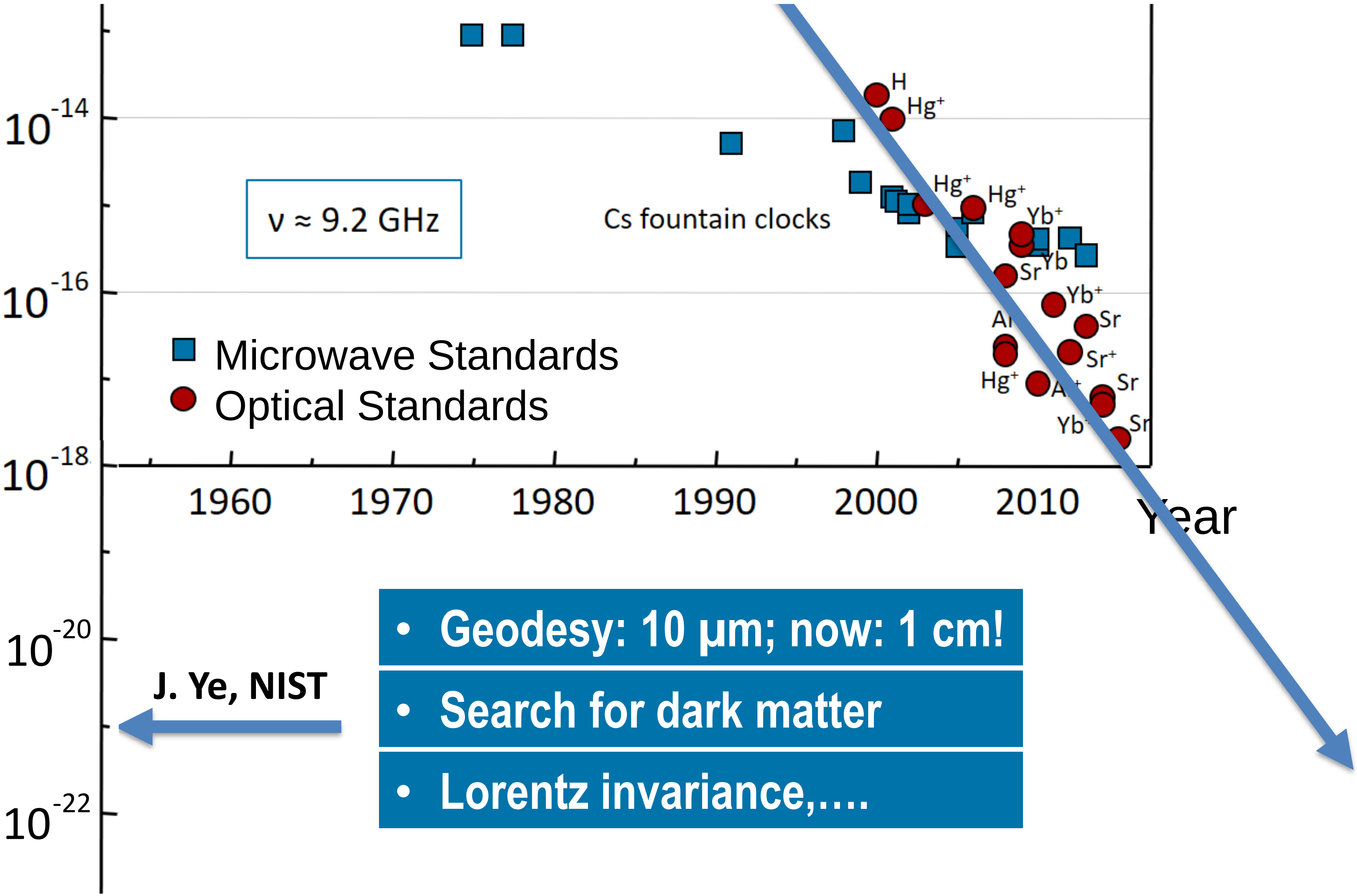
Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks

B. M. Roberts,[1,*] P. Delva,[1] A. Al-Masoudi,[2] A. Amy-Klein,[3] C. Bærentsen,[1] C. F. A. Baynham,[4] E. Benkler,[2] S. Bilicki,[1] W. Bowden,[4] E. Cantin,[1,3] E. A. Curtis,[4] S. Dörscher,[2] F. Frank,[1] P. Gill,[4] R. M. Godun,[4] G. Grosche,[2] A. Hees,[1] I. R. Hill,[4] R. Hobson,[4] N. Huntemann,[2] J. Kronjaeger,[4] S. Koke,[2] A. Kuhl,[2] R. Lange,[2] T. Legero,[2] B. Lipphardt,[2] C. Lisdat,[2] J. Lodewyck,[1] O. Lopez,[3] H. S. Margolis,[4] H. Álvarez-Martínez,[1,5] F. Meynadier,[1,6] F. Ozimek,[4] E. Peik,[2] P.-E. Pottie,[1] N. Quintin,[7] R. Schwarz,[2] C. Sanner,[2,†] M. Schioppo,[4] A. Silva,[4] U. Sterr,[2] Chr. Tamm,[2] R. Le Targat,[1] P. Tuckey,[1] G. Vallet,[1] T. Waterholter,[2] D. Xu,[1] and P. Wolf[1,‡]

[1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France*
[2]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[3]*Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, CNRS, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France*
[4]*National Physical Laboratory, Hampton Road, Teddington TW11 0LW, United Kingdom*
[5]*Sección de Hora, Real Instituto y Observatorio de la Armada, San Fernando, Spain*
[6]*Bureau International des Poids et Mesures, BIPM, Pavillon de Breteuil, 92312 Sèvres, France*
[7]*Réseau National de télécommunications pour la Technologie, l'Enseignement et la Recherche, 23–25 Rue Daviel, 75013 Paris, France*

(Dated: May 21, 2019)

About the future of time

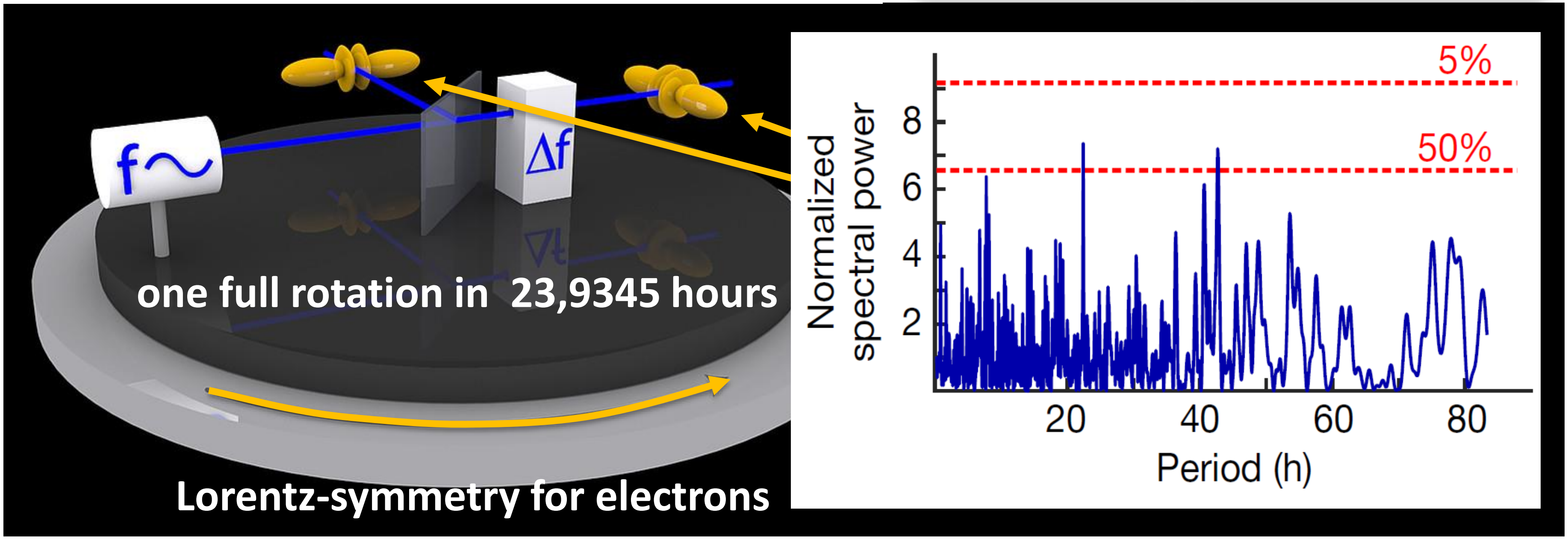


- **Geodesy: 10 µm; now: 1 cm!**
- **Search for dark matter**
- **Lorentz invariance,….**

About the future of time

- **Lorentz invariance,….**

See talk of E. Peik

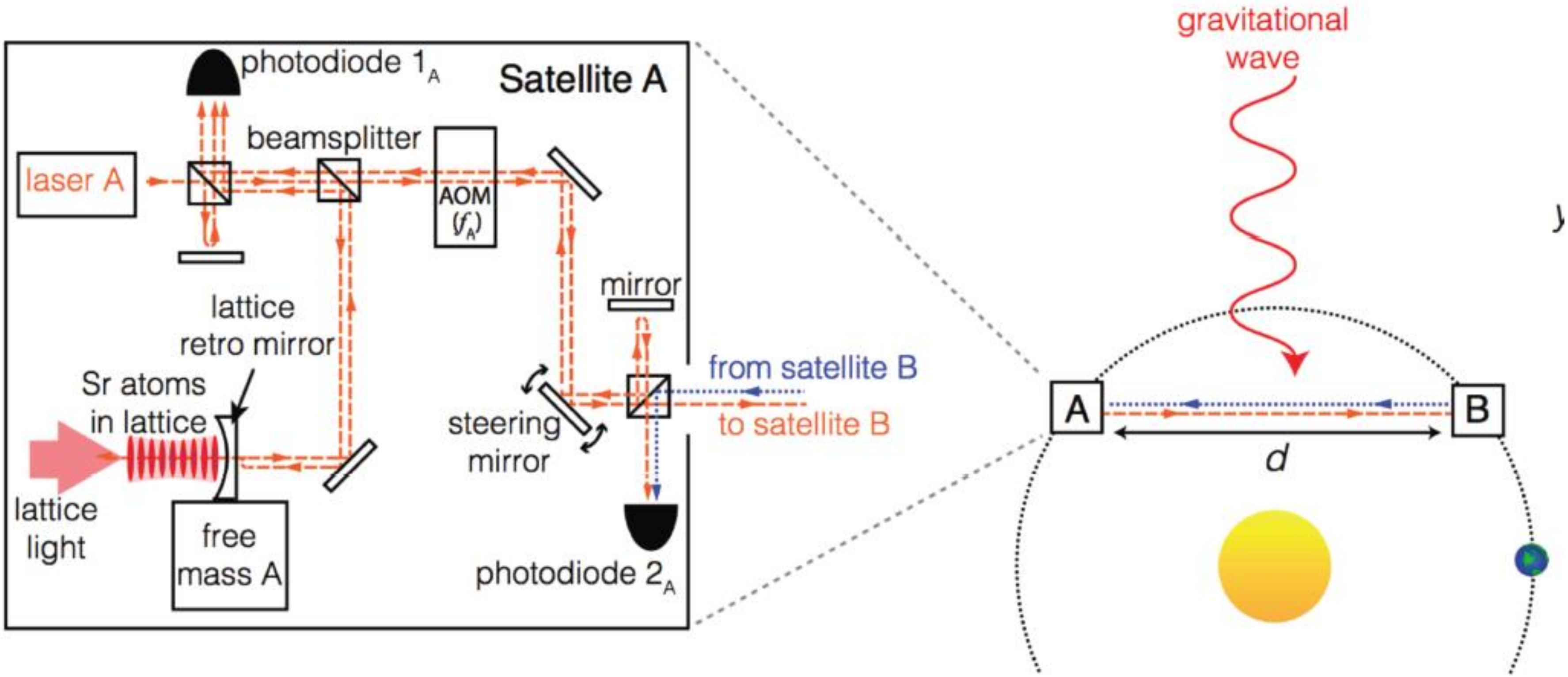


- Frequency comparison over more than 1000 h.
- No relative change for periods of few min - 80 h.

→ relative frequency deviation: < 3 × 10^{-18}

Ch. Sanner, N. Huntemann, R. Lange, Ch. Tamm, E. Peik, Marianna S. Safronova, S. G. Porsev
2 0 4 | N A T U R E | VO L 5 6 7 | 1 4 M A R C H 2 0 1 9

About the future of time



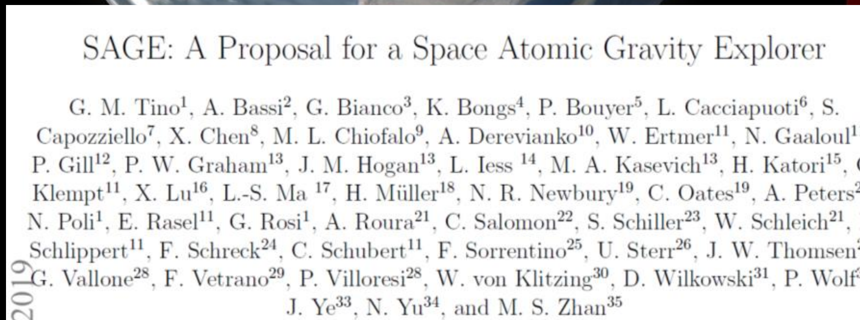
- **Gravitational wave detection**

A dream … that will come true…

Optical clocks at ~10^{-19} relative uncertainty in space!

Proposal to ESA in 2016

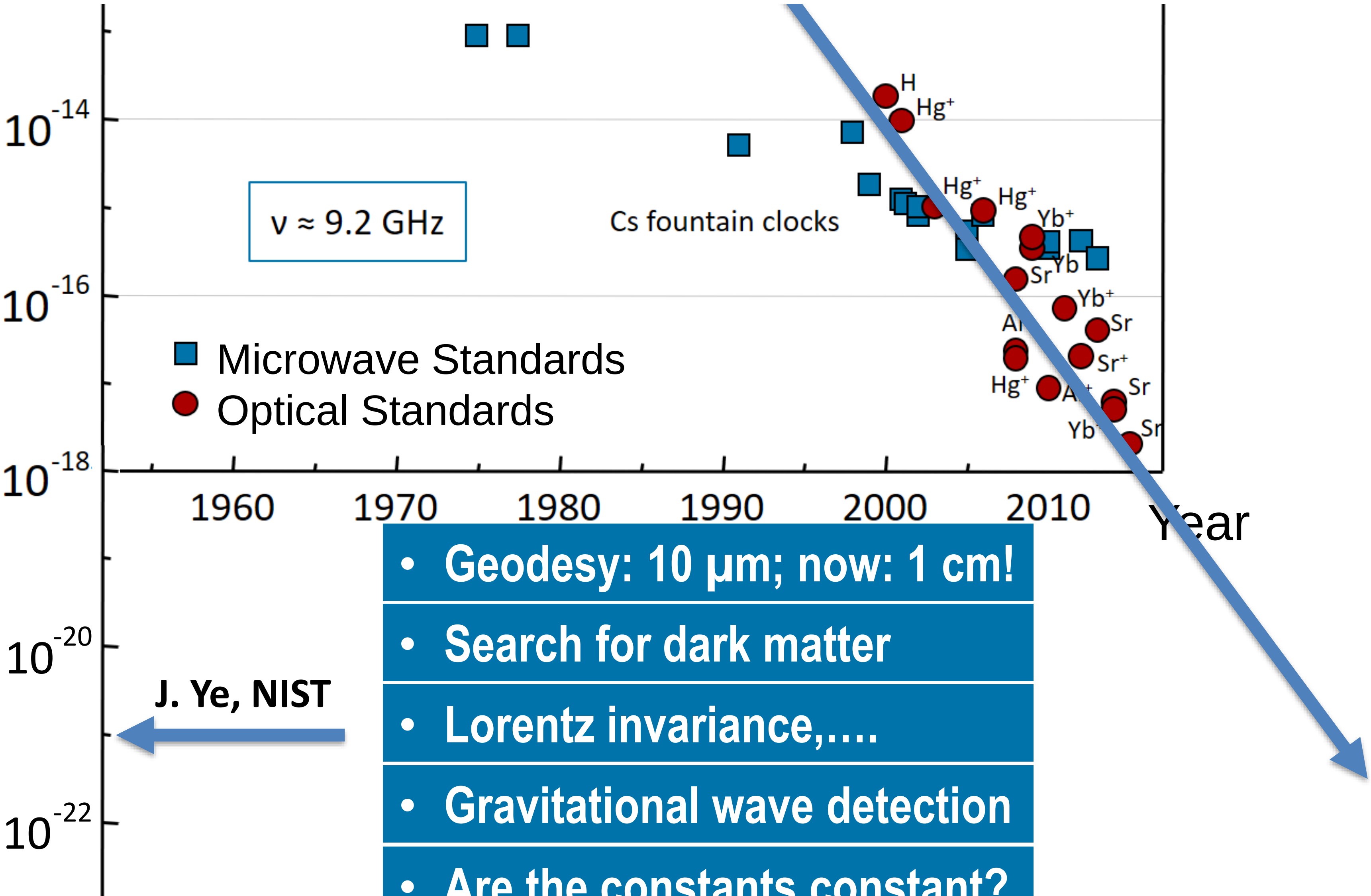
…a multi-satellite configuration with payload/instruments including strontium optical atomic clocks, strontium atom interferometers, satellite-to-satellite and satellite-to-Earth laser links.


SAGE: A Proposal for a Space Atomic Gravity Explorer

G. M. Tino[1], A. Bassi[2], G. Bianco[3], K. Bongs[4], P. Bouyer[5], L. Cacciapuoti[6], S. Capozziello[7], X. Chen[8], M. L. Chiofalo[9], A. Derevianko[10], W. Ertmer[11], N. Gaaloul[1 P. Gill[12], P. W. Graham[13], J. M. Hogan[13], L. Iess [14], M. A. Kasevich[13], H. Katori[15], Klempt[11], X. Lu[16], L.-S. Ma [17], H. Müller[18], N. R. Newbury[19], C. Oates[19], A. Peters N. Poli[1], E. Rasel[11], G. Rosi[1], A. Roura[21], C. Salomon[22], S. Schiller[23], W. Schleich[21], Schlippert[11], F. Schreck[24], C. Schubert[11], F. Sorrentino[25], U. Sterr[26], J. W. Thomsen G. Vallone[28], F. Vetrano[29], P. Villoresi[28], W. von Klitzing[30], D. Wilkowski[31], P. Wolf J. Ye[33], N. Yu[34], and M. S. Zhan[35]

2019

About the future of time

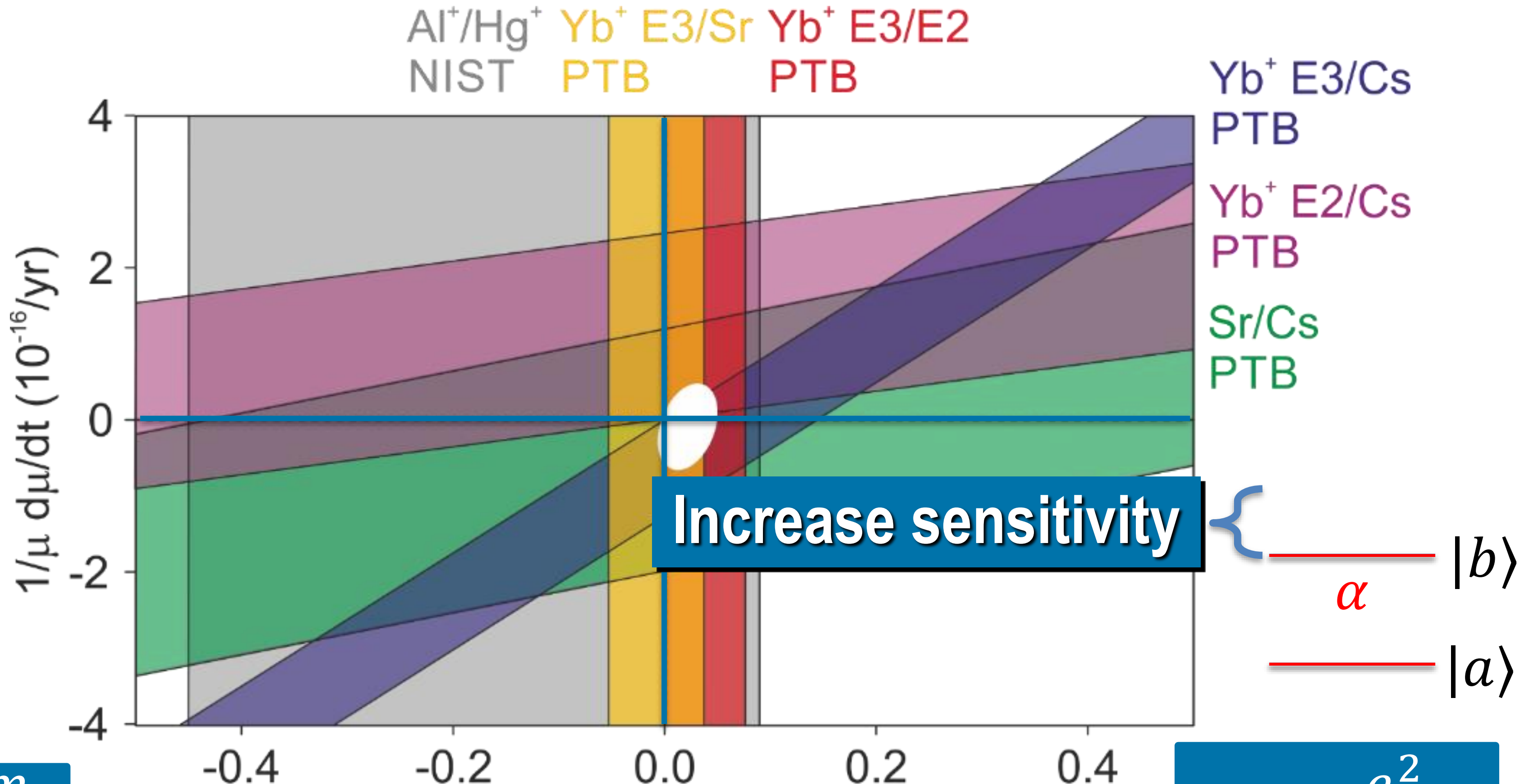


- Geodesy: 10 µm; now: 1 cm!
- Search for dark matter
- Lorentz invariance,….
- Gravitational wave detection
- Are the constants constant?

Are the constants constant?

→ $\frac{1}{\mu}\frac{d\mu}{dt} = -1.2(5.8)\times 10^{-17}/\mathrm{yr}$

→ $\frac{1}{\alpha}\frac{d\alpha}{dt} = 2.3(2.8)\times 10^{-18}/\mathrm{yr}$



Increase sensitivity

|b⟩

α

|a⟩

$\mu = \frac{m_e}{m_P}$

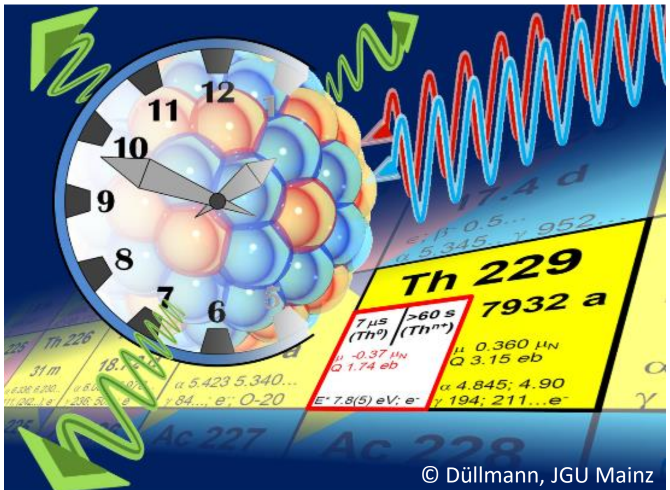
Can we do even better?

$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$

Are the constants constant?

See talk of E. Peik

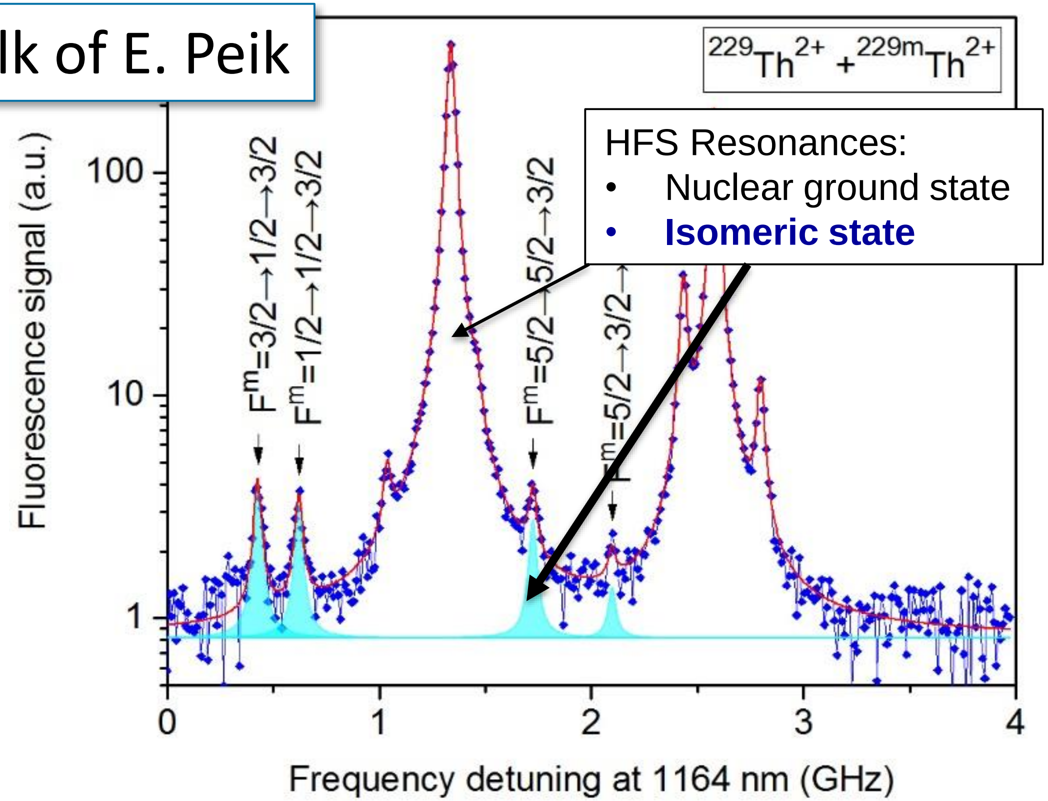
Nuclear Transition



$\Delta f/f \sim 10^{-19}$

$\Delta\alpha/\alpha < 10^{-20}$ /a

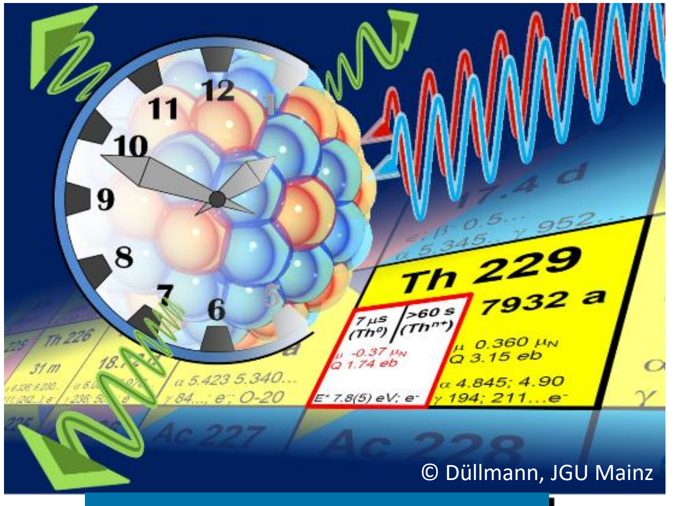
Enhancement: 0…10 000



- **First optical detection of the isomer**
- **Nuclear moments of the isomer**
- **Charge radius of the isomer**

Are the constants constant?

Nuclear Transition



$\Delta f/f \sim 10^{-19}$

$\Delta\alpha/\alpha < 10^{-20}$ /a

Enhancement: 0…10 000

Highly Charged Ions

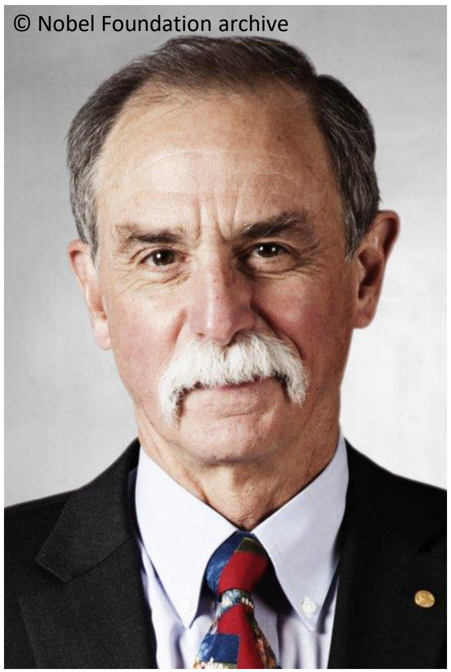
$\Delta f/f \sim 10^{-19}$

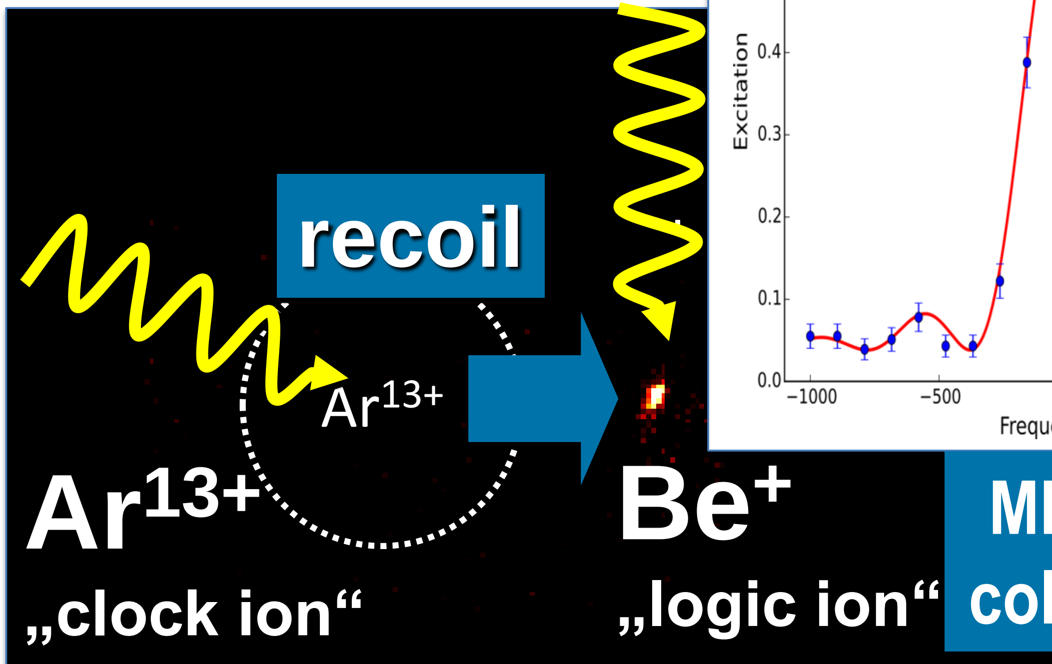
$\Delta\alpha/\alpha < 10^{-20}$ /a

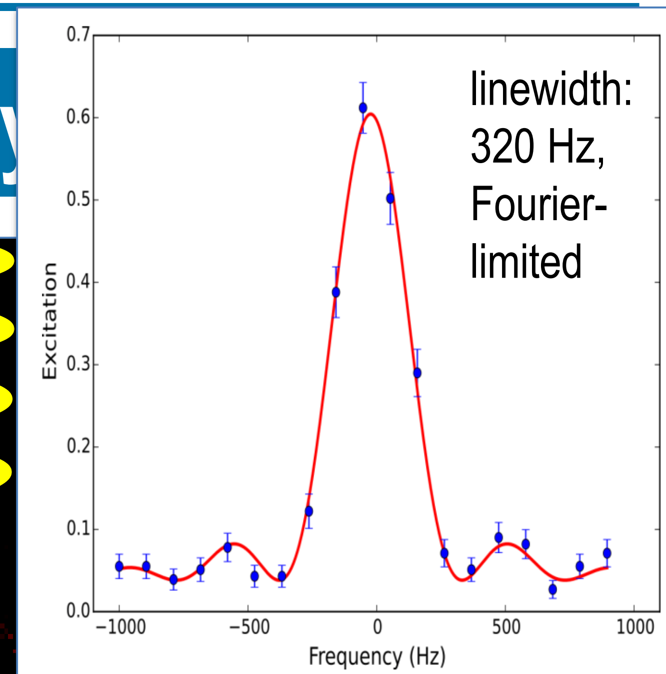
Enhancement: ~< 100

Are the constants constant?

Quantum logic spectroscopy





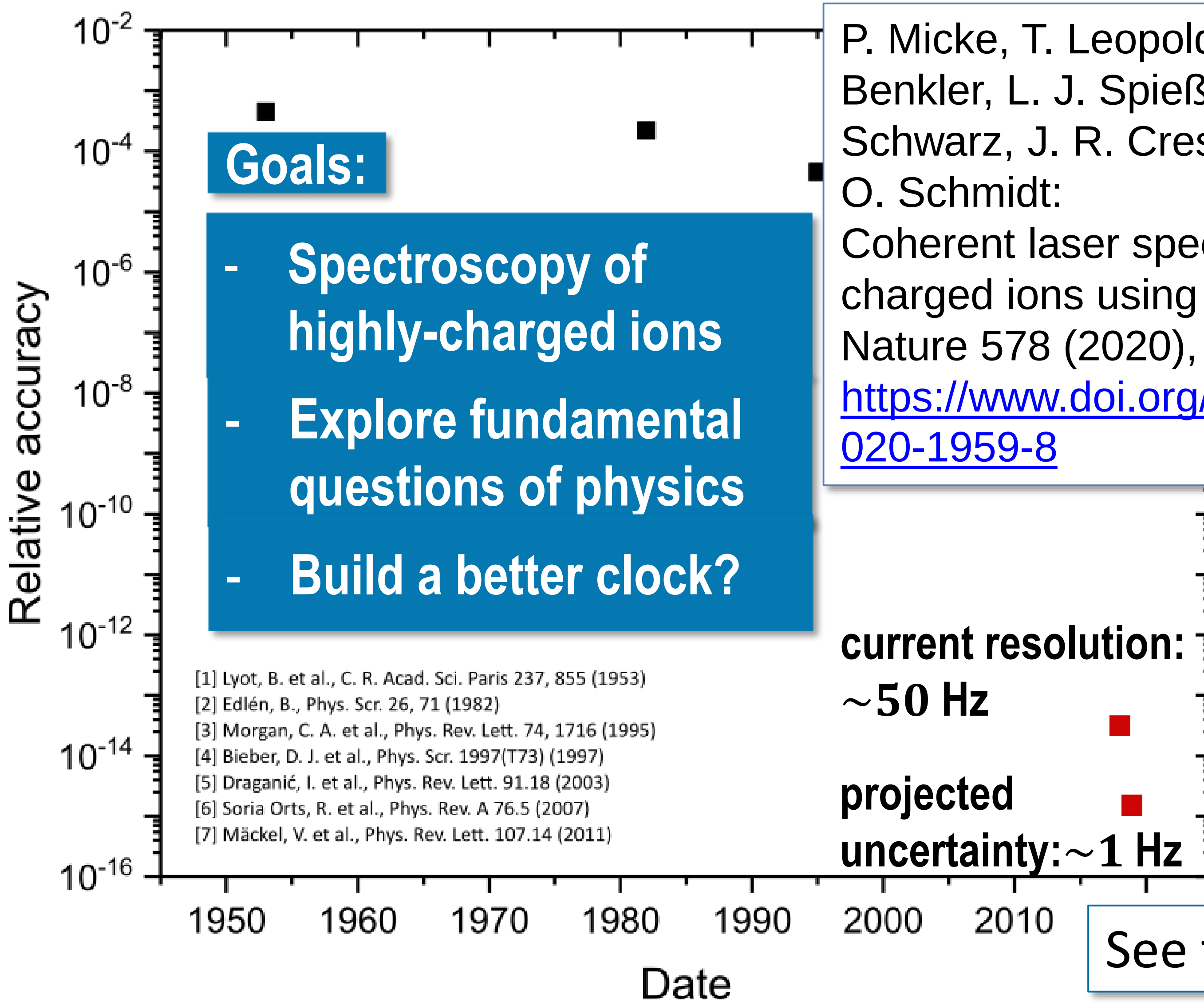


MPIK – PTB collaboration

<u>Nobel Price 2012:</u> Dave Wineland & Serge Haroche

“for ground-breaking experimental methods to manipulate and investigate individual quantum systems”

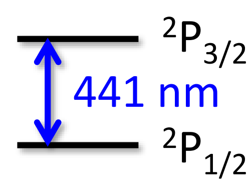
Are the constants constant?



Goals:

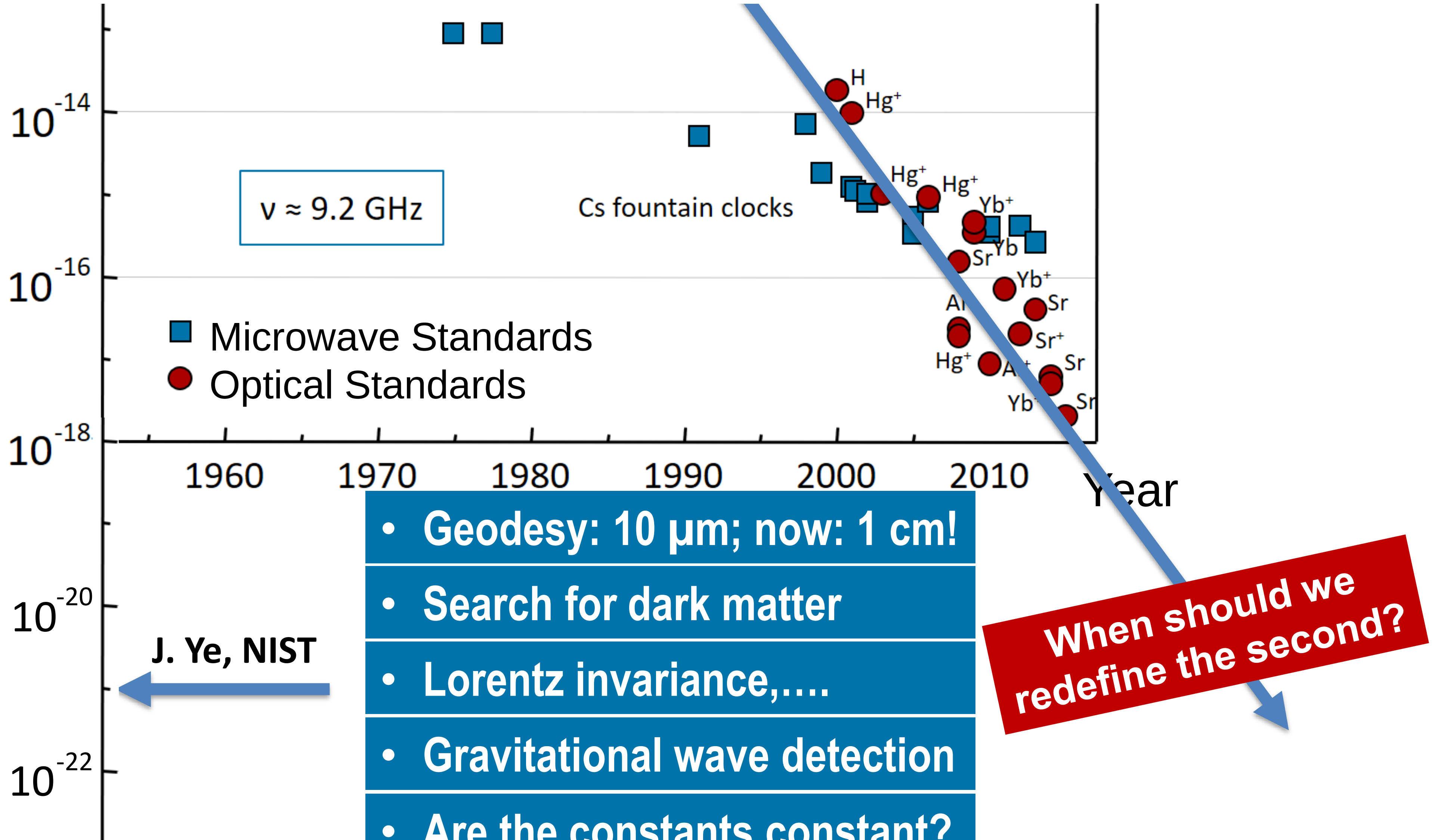
- Spectroscopy of highly-charged ions
- Explore fundamental questions of physics
- Build a better clock?

P. Micke, T. Leopold, S. A. King, E. Benkler, L. J. Spieß, L. Schmöger, M. Schwarz, J. R. Crespo López-Urrutia, P. O. Schmidt:
Coherent laser spectroscopy of highly charged ions using quantum logic.
Nature 578 (2020), DOI: https://www.doi.org/10.1038/s41586-020-1959-8



See talk of P. Schmidt

About the future of time



- Geodesy: 10 µm; now: 1 cm!
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- Are the constants constant?

About the future of time: CC-TF Roadmap

3 clocks
$\Delta\nu_i/\nu_i \sim 10^{-18}$

Uncertainties: ~ two orders of magnitude better than Cs

3 comparisons
$\Delta(\nu_i/\nu_j) < 5 \times 10^{-18}$

Independent measurements of the same optical clock in different institutes

3 clocks
$\Delta\nu/\nu < 3 \times 10^{-16}$

Continuity … definition: independent measuremen… endent Cs primary clocks

Regular contribut. to TAI

Measurement reports cover… ys

2 comp. betw. 5 clocks
$\Delta(\nu_i/\nu_k) / (\nu_i/\nu_k) < 5 \times 10^{-18}$

Frequency ratios

… only time will tell…

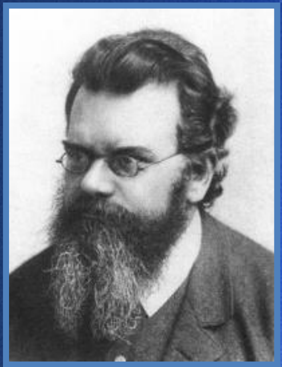
Validation and decision for optical standard

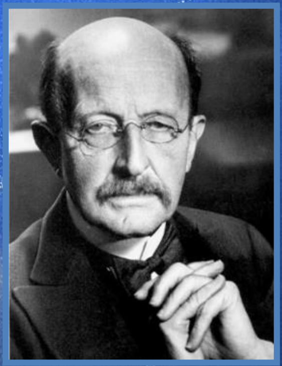
CGPM

CCTF Strategy Document, Annex 1

2017 2020 2025 2030

SI International System of Units





…approaching the most abstract definition of units...

End